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Beach Profile Changes: East Coast of Lake Michigan, 1970-72

by

R.A. Davis, W.G. Fingleton, and P.C. Pritchett

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The primary result of this field study of beach changes on the eastern shore of Lake Michigan concerned the movement of the bluff or the edge of the terrace marking the landward boundary of the beach. Data collected every 4 weeks from August 1970 to August 1972 indicated recession or no change at each of 17 profile sites on a 250-mile segment of the east coast of Lake Michigan. During this period, lake levels were rising from a mean of 578.9 feet above mean water level (MWL) in 1970 to 579.7 feet MWL in 1972. The

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20. Abstract. (Continued)

maximum bluff erosion at any one site between monthly surveys was 20 feet at profile 4 in June 1972. Variables affecting the rate of movement of the bluff include lake level, composition of the bluff or terrace, orientation and straightness of shoreline, wave climate, manmade structures, and possibly longshore bars. There was a lack of correlation between bluff erosion at nearby stations, but each site varied seasonally with maximum erosion occurring in late fall when storm occurrence is also high. Shore ice protected the beaches in winter; erosion resumed in spring at a reduced level. Beach width from the base of the bluff to the water level at the time of the survey also varied seasonally, with beaches narrow in early summer when lake level is at a maximum and wider in late fall when lake level is at a lower level. The study beaches were mostly well-sorted sand (mean grain size between 0.330 to 0.189 millimeter or 1.60 and 2.40 phi units) with some gravel and heavy mineral concentrations.

PREFACE

This report is published to provide coastal engineers with reliable profile and sediment data collected during a 2-year study of beach changes along a 250-mile segment of the eastern shore of Lake Michigan. The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

The data for the report were collected under CERC Contract No. DACW72-70-C-0037 with Western Michigan University (WMU), Kalamazoo, Michigan. Professor R.A. Davis, while at WMU was the principal investigator, assisted by WMU graduate students, particularly W. George Fingleton, who was in charge of data collection during the second year.

The report was prepared from earlier drafts of Professor Davis by P.C. Pritchett, while at CERC, under the supervision of C.J. Galvin, Jr., Chief, Coastal Processes Branch, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JAMES L. TRAYERS
Colonel, Corps of Engineers
Commander and Director

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BEACH PROFILE CHANGES: EAST COAST OF LAKE MICHIGAN, 1970-72

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I. INTRODUCTION

1. Nature and Purpose.

This study was initiated to collect profile and sediment data that would delineate spatial and temporal variations in beach changes, to correlate these changes to other variables and to particularly identify the effect of long-term lake level changes. This report focuses on the erosion (recession) of the dunes or bluffs (expressed in horizontal feet of landward movement) and examines the relation between this erosion, or the absence of any erosion, and seasonal and annual fluctuations in weather, waves, and lake level during the study period. Throughout this report the term *erosion* refers to a loss of sediment from the area behind the beach, i.e., the dune, bluff, or foredune terrace.

2. Previous Studies.

The processes and sediments of the eastern shore of Lake Michigan have previously been investigated. Characteristics of beach sediments were analyzed by Hough (1935) and Hulsey (1962). Coastal geomorphology, especially longshore bars and troughs, was studied by Evans (1939) and by Saylor and Hands (1970). Few studies are available on the collection and analysis of beach profile data. Powers (1958) and Brater and Seibel (1971) compiled bluff erosion rates for selected sites. A significant correlation between bluff erosion rates and lake levels was the result of a survey using aerial photos and site visits along Lakes Michigan and Huron by Seibel (1972). Systematic profiling studies and time-series studies of beach processes along Lake Michigan are reported in Davis and Fox (1971), and Fox and Davis (1970b, 1971a).

3. Study Area.

The 17 profile sites discussed in this report are located in the State of Michigan along the eastern coast of Lake Michigan between Point Betsie in the north and Lakeside in the south (Fig. 1). The sites, approximately 15 miles apart, were chosen by location and year-round accessibility. However, the sites exhibit a variety of coastal morphology, composition, and shoreline orientation.

Each of the 17 sites is shown by a figure which includes: vertical and oblique photos with profile lines indicated; a brief description of the geomorphology; location including the section, tier, range, and

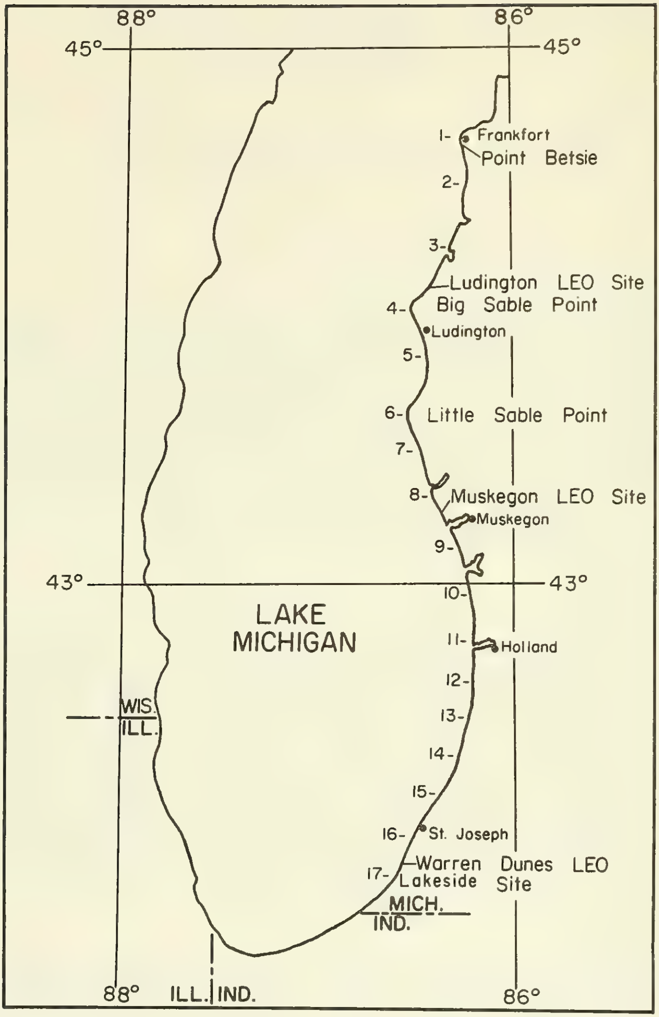


Figure 1. Index map showing profile locations along the eastern shore of Lake Michigan.

quarter according to the method by U.S. Public Land Surveys; and a description of the bench mark location. The datum for each profile is referenced to the lake level as recorded at Holland, Michigan, on 3 August 1970. This level, 579.40 feet above mean sea level (MSL), is assumed to be the same at all locations. Azimuths of each profile are given below:

Profile Site	Azimuth
1	288°
2	281°
3	250°
4	277°
5	265°
6	277°
7	252°
8	246°
9	245°
10	259°
11	270°
12	280°
13	277°
14	295°
15	305°
16	296°
17	317°

II. WIND AND WAVE CLIMATE

1. Winds and Storms.

Wind and precipitation are important meteorological variables affecting the beaches of the Great Lakes. Winds generate the waves which break on the beaches, while the precipitation and ensuing drainage affect the lake level which determines the position on the beaches where the waves will break. Figure 2 shows the number of 24-hour periods from 1960 to 1970, when winds $\geq$ 20 miles per hour occurred, as measured at the Muskegon Weather Bureau Station and tabulated by Seibel (1972). During this time, 92 percent of the 24-hour periods of $\geq$ 20-miles-per-hour winds occurred from November through April, and were predominantly from the south, southwest, west, and northwest. Winds from these directions generate waves that are directed toward the east coast of Lake Michigan. For most sites, the fetch of these winds is smallest when winds are westerly, and larger for south, southwest, and northwest winds.

Storm systems generally cross Lake Michigan in a west to east direction and move onshore in the study area. While winter storms appear to be the most severe, they have little affect on the beaches because of protection afforded by lake ice. Spring and fall storms cause most changes to the beaches although a storm in the summer of 1969 eroded a cliff about 12 feet in 48 hours near Stevensville, Michigan (Fox and Davis, 1970b).

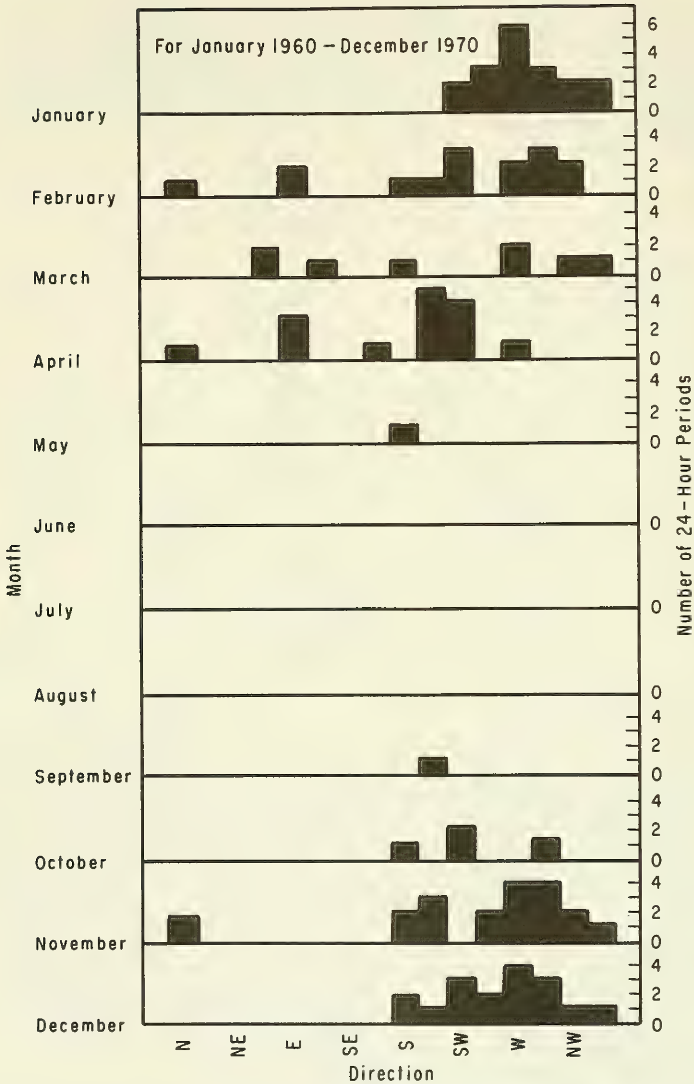


Figure 2. Number of 24-hour periods in which winds equaled or exceeded 20 miles per hour at Muskegon.

2. LEO Data.

Wave and beach data from sites at Ludington, Muskegon, and Warren Dunes (Fig. 1) are given in Tables 1, 2, and 3. The data are systematically collected as part of the CERC Littoral Environment Observation (LEO) program (Berg, 1968). The Lake Michigan observations, made by State park rangers, are a joint effort by CERC, the U.S. Army Engineer District, Detroit and the State of Michigan Department of National Resources. Data from the ice-free months of 1972 have been tabulated by Bruno and Hiipakka (1973). Daily observations consist of visual estimates of height, period, direction, and type of breaking waves, width of the surf zone, direction and windspeed as measured by a Dwyer wind meter, direction and rate of longshore current as indicated by a dye patch, and a measure of foreshore slope with a level or an inclinometer. Surface sediment samples are collected in the swash zone at monthly intervals.

Breaker height is lowest in summer and highest in fall which agrees with the wind data in Figure 2. Longshore current direction, dominantly to the south at Warren Dunes and mixed at the other two sites, is consistent with the open water fetches of these sites (Fig. 1).

3. Lake Level.

Precipitation and runoff changes cause both long-term and annual fluctuations in the level of Lakes Michigan and Huron which are hydrologically a single unit. Other factors affecting the lake level are the rate of flow from Lake Superior and the outflow to Lake Erie. However, the dominant factor is precipitation. A plot of lake level and precipitation from 1900 to 1972 (Seibel, 1972), shows a high degree of correlation between the two curves.

Long-term changes may have a range of several feet. Average lake levels for 1960-72, as measured by the Huron-Michigan "master" gage at Harbor Beach, Michigan, are shown in Figure 3. Lowest recorded lake levels in the past 112 years occurred in March 1964, and were preceded by a period of high levels in the early 1950's.

Annual fluctuations are usually about 1 foot and predictable. Minimum annual level is generally in February and March and the maximum in summer (Fig. 4), reflecting both precipitation and runoff. Winter runoff is negligible due to low temperatures which keep the moisture in the form of snow and ice.

4. Ice Formation.

Although Lake Michigan does not freeze over completely, ice usually forms along the shores of the study area during a normal winter. Freezeup begins in late December in the northern part of the lake and ice accumulates in a southerly direction along the shorelines. Maximum ice cover occurs

Table 1. Warren Dunes State Park (Lake Michigan); Littoral Environment Observation Program (1972).

Wave and Beach Data	Month						
	May	June	July	August	September	October	November
Breaker period (seconds)							
Average	3.6	4.2	3.2	4.0	4.1	4.5	4.5
Standard deviation	0.9	1.5	0.9	2.3	1.0	1.1	0.7
Breaker height (meters)							
Average	0.24	0.39	0.20	0.36	0.40	0.40	0.41
Standard deviation	0.28	0.41	0.25	0.35	0.32	0.36	0.34
Breaker angle (degrees)							
Average	92	96	90	90	88	88	87
Standard deviation	21	12	16	12	13	9	9
Breaker type (percent occurrence)							
Calm	29	28	20	11	11	26	21
Spill	24	36	27	25	4	0	0
Plunge	0	8	3	4	7	26	29
Surge	24	8	40	21	22	26	18
Spill-plunge	24	20	10	39	56	23	32
Foreshore slope (degrees)							
Average	9	7	9	7	6	6	7
Standard deviation	2	3	2	3	2	2	1
Width of surf zone (meters)							
Average	16	21	12	8	6	5	8
Standard deviation	9	42	9	7	6	4	4
Current speed (meters per second)							
Average	0.13	0.18	0.12	0.25	0.28	0.24	0.28
Standard deviation	0.14	0.19	0.12	0.27	0.23	0.23	0.29
Average Velocity (+ right and - left)	-0.07	-0.15	-0.03	-0.09	-0.15	-0.02	-0.09
Sand size (phi)							
Average	1.58	1.24	-----	1.45	1.47	1.36	1.16
Standard deviation	0.37	0.25	-----	0.39	0.29	0.28	0.51

(from Bruno and Hiipakka, 1973)

Table 2. Muskegon State Park (Lake Michigan); Littoral Environment Observation Program (1972).

Wave and Beach Data	Month						
	May	June	July	August	September	October	November
Breaker period (seconds)							
Average	3.4	3.8	2.7	3.8	3.9	4.9	4.7
Standard deviation	1.3	1.0	0.7	1.3	1.2	1.4	1.1
Breaker height (meters)							
Average	0.28	0.44	0.35	0.45	0.58	0.68	0.59
Standard deviation	0.26	0.35	0.31	0.45	0.34	0.46	0.36
Breaker angle (degrees)							
Average	96	103	87	88	95	99	102
Standard deviation	33	30	14	16	20	19	17
Breaker type (percent occurrence)							
Calm	21	14	19	16	4	10	7
Spill	7	28	16	6	32	32	25
Plunge	0	0	3	0	16	6	11
Surge	57	48	48	35	28	26	29
Spill-plunge	14	10	13	42	20	26	29
Foreshore slope (degrees)							
Average	11	11	13	12	10	11	10
Standard deviation	2	3	4	5	2	3	2
Width of surf zone (meters)							
Average	3	31	48	26	24	41	27
Standard deviation	4	28	37	30	16	46	22
Current speed (meters per second)							
Average	0.12	0.19	0.09	0.18	0.20	0.30	0.22
Standard deviation	0.18	0.27	0.08	0.22	0.21	0.30	0.20
Average velocity (+ right and - left)	-0.05	-0.13	0.05	0.07	0.07	0.15	-0.06
Sand size (phi)							
Average	1.43	1.34	1.12	1.27	1.39	1.26	1.43
Standard deviation	0.28	0.28	0.30	0.24	0.27	0.26	0.29

(from Bruno and Hiipakka, 1973)

Table 3. Ludington State Park (Lake Michigan); Littoral Environment Observation Program (1972).

Wave and Beach Data	Month				
	May	July	August	September	October
Breaker period (seconds)					
Average	3.3	3.1	3.7	4.2	4.7
Standard deviation	1.0	0.6	0.9	0.9	1.7
Breaker height (meters)					
Average	0.18	0.36	0.47	0.78	0.97
Standard deviation	0.11	0.25	0.44	0.50	0.59
Breaker angle (degrees)					
Average	118	88	86	91	96
Standard deviation	36	21	15	23	20
Breaker type (percent occurrence)					
Calm	13	10	13	0	0
Spill	31	40	22	6	40
Plunge	31	30	26	6	5
Surge	25	0	9	19	15
Spill-plunge	0	20	30	69	40
Foreshore slope (degrees)					
Average	10	9	9	10	9
Standard deviation	1	2	2	2	2
Width of surf zone (meters)					
Average	0	9	10	5	55
Standard deviation	0	21	17	3	57
Current speed (meters per seconds)					
Average	0.10	0.25	0.31	0.24	0.40
Standard deviation	0.06	0.26	0.38	0.23	0.31
Average velocity (+ right and - left)	-0.04	0.17	0.17	0.13	0.01
Sand size (phi)					
Average	1.54	1.37	1.46	1.49	-----
Standard deviation	0.30	0.26	0.27	0.23	-----

(from Bruno and Hiipakka, 1973)

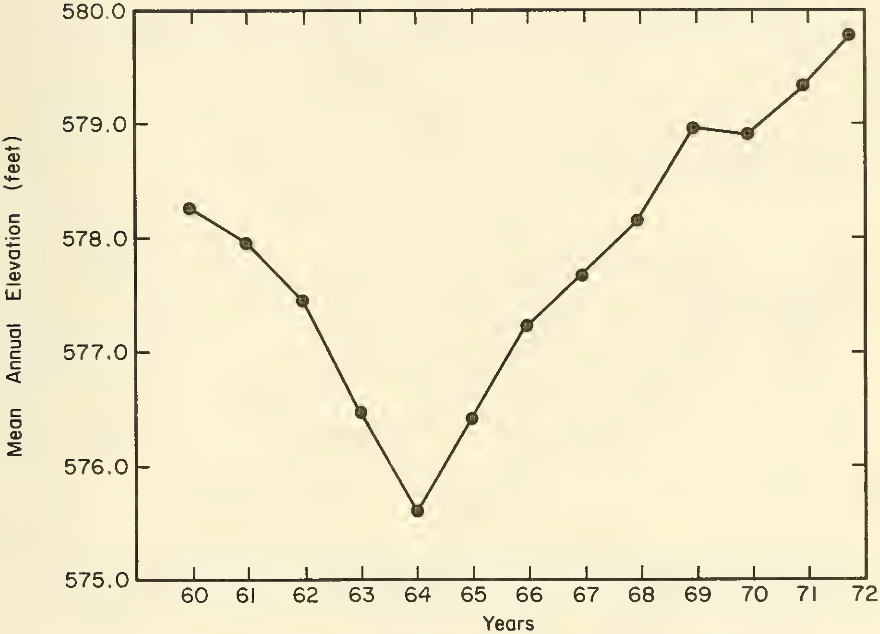


Figure 3. Mean annual elevations at Harbor Beach, Michigan, 1960 to 1972 (feet above mean water level at Father Point, Quebec).

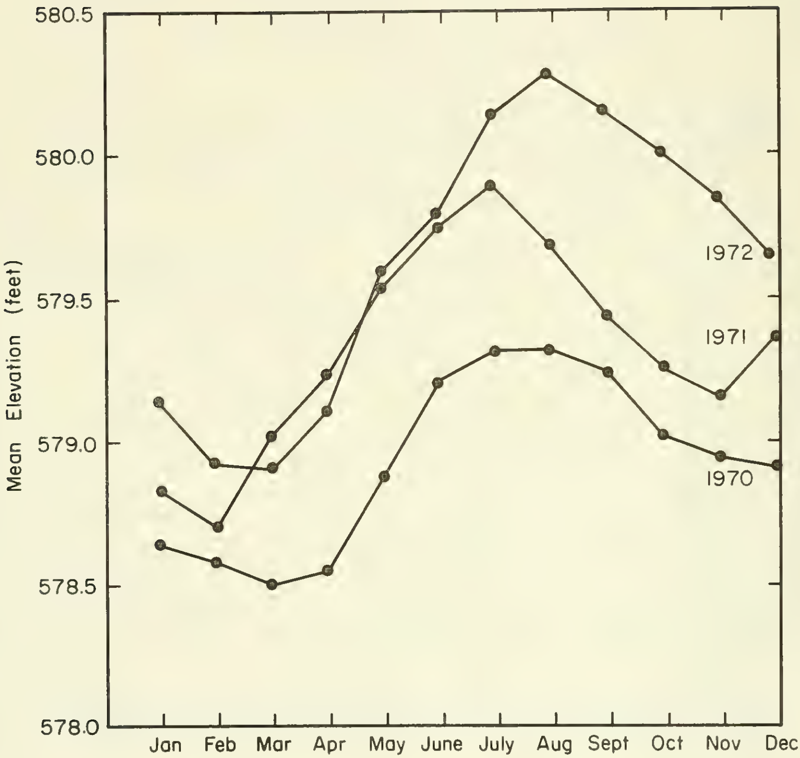


Figure 4. Monthly mean elevation at Harbor Beach, Michigan, (feet above mean water level at Father Point, Quebec).

in late February or early March but melts quickly; by early April most of the ice is gone. About 10 percent of the lake surface is ice-covered during a mild winter, 40 percent during a normal winter, and 80 percent during a severe winter (Rondy, 1969). Current patterns in southern Lake Michigan distribute ice floes along the shore; even during a mild winter shoreline ice may extend 10 to 15 miles offshore. Onshore winds sometimes drive the ice onto the shore causing beach and property damage.

III. COASTAL AND BEACH MORPHOLOGY

1. Geomorphology of Eastern Lake Michigan.

The Lake Michigan basin was formed by glacial erosion of bedrock and preglacial stream erosion. The eastern shoreline of Lake Michigan is underlain by Pleistocene glacial drift and characterized by reworked glacial sediment; there is no rock exposure in the area. Shoreline orientation changes from east-west in the south end to a general north-south direction throughout most of the area. Little Sable Point, Big Sable Point, and Point Betsie (Fig. 1) protrude westward interrupting the general shoreline trend. Elevations along the shore range from 580 feet to about 850 feet above sea level (Hulsey, 1962), or from 0 to about 270 feet above lake level.

Profile sites are located adjacent to till bluffs, lake sands, active dunes, and densely vegetated dunes. At the onset of the study, terraces of lake sands, referred to as foredune terraces, extended seaward from the dune or bluff at nearly every location except where active dunes were present or till bluffs reached the beach. These terraces, recent deposits containing beer cans and other recognizable human artifacts, had accumulated during recent periods of low lake level. In the 2-year study period many of these foredune terraces eroded and waves had access to the dune or bluff.

The volume of sediment along eastern Lake Michigan appears to be generally small. At a few locations glacial till crops out in the breaker zone after severe storm erosion. The direction of net longshore transport (Fig. 5) is based on conclusions from a beach sediment study by Hulsey (1962), which considered such indicators as occurrences of mineral types, geographic distribution of mean grain size, accumulations of sand at littoral barriers, and wind and wave climate. The indicated net transport south of Holland is southward, north of Holland northward, and mixed between Little and Big Sable Points (Fig. 5).

2. Beach Morphology.

Geometry of Lake Michigan beaches is similar to tidal areas; beach profiles show a rather horizontal backshore area and a nearly planar, lakeward-sloping foreshore zone or beachface. During severe erosion the beach profile may be a continuous, slightly concave upward foreshore surface. A plunge step (small scarp) is commonly developed and marks the lakeward margin of the beach except during high energy conditions. After

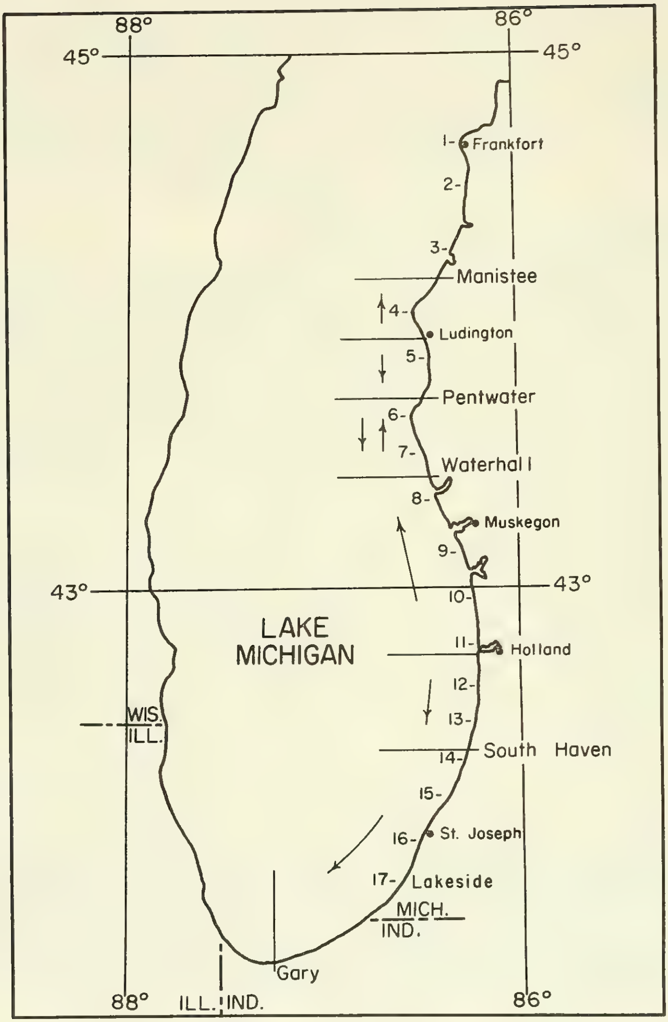


Figure 5. Direction of net longshore transport (Hulsey, 1962).

storm erosion, shallow nearshore sandbars (ridge and runnel topography) (King and Williams, 1949) are common and may migrate shoreward eventually welding to the beach (Davis, in preparation, 1975). Brief descriptions of the geomorphology at the 17 sites are included in Section V of this report.

IV. METHOD

1. Profiling Method.

The technique for measuring beach profiles is essentially that described by Emery (1961). The only equipment used is a pair of wooden stakes, 5 feet long and graduated at 0.1-foot intervals. The method requires at least two persons although it is desirable to have a third to record the data.

The survey was started at a bench mark using a metal pipe or wooden stake. The height of the stake above ground level was noted to recognize any accumulation or erosion to the surface adjacent to the stake. The direction of the profile (perpendicular to the beach) was visually approximated. Horizontal distances were measured with a 5-foot stake, and topographic changes less than 5 feet in horizontal distance were recorded to the nearest foot. Vertical changes were determined by lining up the horizon with the top of the lakeward stake and noting the difference to the nearest 0.05 foot on the landward stake. Horizontal changes were referenced to the bench mark; vertical measurements were referenced to the lake level at the time of the first survey which was 579.4 feet MWL. Measurements were made by a hand level in case of fog or ice ridges which could prohibit sighting of the horizon.

2. Profiling Format and Dates Visited.

Each of 17 beach sites was visited once every 4 weeks, and the routine for data collection remained fairly constant. The basic format was as follows:

(a) Location of the monument and determination of the need of an auxiliary stake if the permanent stake was in danger of removal by erosion.

(b) Profiling the beach to the plunge step, if possible, using the technique by Emery (1961). During late fall storms it was sometimes impossible to profile to the desired terminus.

(c) As each profile was surveyed, notations were made of topographic and sedimentologic features on the profile. These included small wave-cut features, ridge and runnel development, gravel accumulation, heavy mineral concentrations, and driftwood or other debris.

(d) Color slides were taken of all sites during each visit from about 100 feet south of the profiles. The slides recorded the overall character of the site at each visit.

Dates of the visits to the 17 sites, spaced at approximately 4-week intervals, are listed below:

1970	1971	1972
3 to 5 August	15 to 17 January	15 to 17 January
28 to 29 August	12 to 13 February	12 to 13 February
26 to 27 September	12 to 14 March	10 to 12 March
24 to 25 October	9 to 11 April	7 to 8 April
21 to 22 November	9 to 11 May	6 to 7 May
18 to 20 December	2 to 4 June	4 to 6 June
	30 June to 2 July	30 June to 1 July
	2 to 3 August	
	26 to 28 August	
	24 to 26 September	
	22 to 24 October	
	19 to 20 November	
	20 to 21 December	

3. Data Limitations.

An office and field analysis of the Emery (1961) method of surveying (Czerniak, 1973) indicated a possibility of cumulative error that could result in the seaward end of the measured profile being displaced up to 1 foot vertically from the actual profile. There was also a problem reestablishing some of the bench marks which had disappeared between surveys. For these reasons, only gross changes could reliably be analyzed, and only those changes on the landward end of the profile would be sufficiently accurate to quantitatively evaluate. Therefore, this report is limited to an evaluation of the recession of the dune or bluff, although beach-change trends may be discussed for particular profiles or beach widths.

4. Sediment Sampling and Analysis.

Beach sediments were collected at backshore and foreshore positions at each of the sites during each visit. Samples were taken only in the sand beach to avoid gravel. If the beach was all gravel, no sample was collected. All samples were collected from an undisturbed area along the profile traverse and the location noted on the data sheet. A flat-sided aluminum container was carefully scraped across the sediment surface to collect only the upper 2 or 3 millimeters. About 30 to 50 grams of sediment were collected, placed in watertight plastic bags, and labeled with locations and dates.

Beach samples, oven-dried and split with an Otto Microsplitter to a 12- to 15-gram sample, were used for analysis in the rapid sediment

analyzer (RSA). Of the sample, 5 to 7 grams were inserted in the settling tube and a cumulative curve was produced on the recorder. After a second part of the sample was run a comparison was made between the curves. If both curves were similar, the first one was analyzed; if they were different, another part of the sample was analyzed and the average value of the three curves was used. Mean grain size, sorting, and skewness were determined by the graphic method, using the 16-, 50-, and 84-percentile values from the RSA curves.

V. PROFILE DESCRIPTIONS

The 26 sets of profile data have been computer-plotted and are presented in the Appendix. The bluff or terrace erosion for the 17 profiles during the study period is summarized in Table 4. Descriptions of the changes, vertical and oblique photos, bench mark locations, and geomorphology of the profiles follow.

1. Profile Site 1.

Erosion of the low-lying dunes behind the beach (Fig. 6) was modest during each of the 2 study years. The dunes were cut back 17 feet (7 feet in 1970-71; 10 feet in 1971-72), and all erosion occurred during the fall storm period.

Shortly after breakup of the shore ice in spring, a distinct subaerial ridge and runnel feature, composed almost entirely of imbricated pebbles and small cobbles, was present during both years. The ridge served as excellent protection for the sand bluff during spring storms. The ridge was not breached or destroyed for at least 2 months.

2. Profile Site 2.

This site (Fig. 7) was one of the few where no erosion of the sand bluff occurred during the entire study period. There was some erosion of the beach as evidenced by lag concentrates of heavy minerals. It is possible only to speculate on the lack of erosion since it actually appears to be one of the more likely sites for rapid erosion. The beach is narrow and steep, and an unstable sand bluff extends over 250 feet above the lake immediately behind the beach. The area beginning about 200 yards to the south of the site has also undergone severe bluff erosion and the loss of a dwelling is imminent. The resident of the dwelling has stated that this erosion is the worst in 40 years. Photos from the 1953-54 period of high water show a broad sand terrace and a wide beach fronting the dwelling.

3. Profile Site 3.

The sand terrace at this site (Fig. 8) experienced only 4 feet of recession during 1970-71, and 5 feet the following year. All but 1 foot of this occurred in late fall or early winter during two 4-week periods.

Table 4. Amount of bluff or terrace erosion (feet) at each profile site for each 4-week period during the 2-year study period.

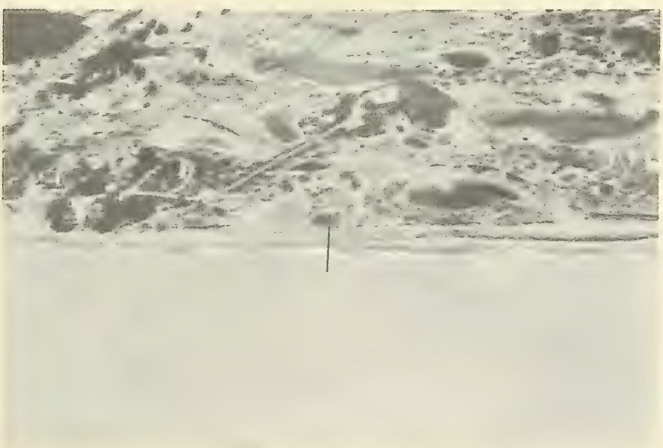
Profile site	Orientation	First year													
		5 Aug.	29 Aug.	27 Sept.	25 Oct.	22 Nov.	20 Dec.	17 Jan.	13 Feb.	13 Mar.	11 Apr.	14 May	4 June	2 July	Total
1	N.13°E.				2	1	4								7
2	N.5°E.														
3	N.27°E.							4							4
4	N.7°E.										2				2
5	N.7°W.					7	11					1			19
6	N.7°E.														
7	N.18°W.			8			8	10					4		30
8	N.24°W.							<1					<1		2
9	N.25°W.											3	3		6
10	N.11°W.			3	4	14	2								23
11	N.3°E.														
12	N.16°E.				2										2
13	N.15°E.						<1								1
14	N.25°E.														
15	N.34°E.														
16	N.28°E.						4					1		<1	5
17	N.43°E.					2	1								3

Profile site	Orientation	Second year													
		2 Aug.	26 Aug.	24 Sept.	22 Oct.	20 Nov.	21 Dec.	15 Jan.	12 Feb.	10 Mar.	8 Apr.	6 May	2 June	1 July	Total
1	N.13°E.				<1	6	4	<1			<1				12
2	N.5°E.														
3	N.27°E.					<1	4	<1					<1	1	6
4	N.7°E.			7	3	2					2	8	20		42
5	N.7°W.													1	1
6	N.7°E.														
7	N.18°W.					<1	5						<1	<1	7
8	N.24°W.						<1	<1			<1				2
9	N.25°W.						3								3
10	N.11°W.			2	2	2	<1	<1							7
11	N.3°E.						2	2							4
12	N.16°E.						8	7							15
13	N.15°E.						2								2
14	N.25°E.														
15	N.34°E.										<1		<1	<1	2
16	N.28°E.														
17	N.43°E.						8							2	10

June 1970

Geomorphology. Site is located at Point Betsie, Michigan, with a shoreline orientation of N.13°E. Coast is comprised of generally stabilized dunes. Beach sediment is sand and gravel with the backshore mostly sand and the foreshore composed of coarse pebbles and cobbles which commonly display imbrication. Beach is one of the highest energy locations in the study area. Occasional gravel berms, and ridge and runnel features are present.

Bench Mark Location (3 August 1970) (NW¼, sec. 4, T.27 N., R.16 W.) On small knoll with scrub bushes, 400 yards south of lighthouse at Point Betsie; azimuth 11°15' from north. Other azimuths (from north): U.S. Coast Guard radio tower, 24°36'; flagpole at ranch house, 116°19'. Bench mark was moved 20 feet landward on 7 April 1972.



11 August 1971

Figure 6. Location and geomorphology of profile site 1.

June 1970

Geomorphology. Beach is located near the Benzie-Manistee County line. Shoreline orientation is N.05°E. and narrow beach is situated just below Inspiration Point. Bluff rises more than 250 feet above lake level and is composed of Pleistocene dunes overlying coastal sands and gravel. Slope is steep and unstable.

Bench Mark Location (3 August 1970) (SW¼, sec. 34, T.25 N., R.16 W.). At base of steep vegetated slope below scenic lookout, a few feet north of large poplar tree. Azimuths (from north): 269°33', large poplar tree; 359°26', Frankfort lighthouse on jetty; 1°30', middle trunk of three poplar trees.

11 August 1971

Figure 7. Location and geomorphology of profile site 2.

June 1970

Geomorphology. Site is adjacent to Bar Lake in Manistee County. Shoreline orientation is N.27°E. Beach is bounded by a terrace of beach and dune sands that rises 10 to 20 feet above the lake. Sediment is mostly sand. Scattered fine gravel sometimes is present in the plunge zone only.

Bench Mark Location (3 August 1970) (SE¼, sec. 24, T.22 N., R.17 W.). On Crescent Beach Road north of Manistee, about 100 feet north of public access beach. Azimuths (from north): 6°10', east margin of larger of two islands; 20°40', corner of house (105'); 41°54', corner of house.

11 August 1971

Figure 8. Location and geomorphology of profile site 3.

In the first year the erosion took place later than normal, between 20 December and the time of ice formation in January. Usually the beach is frozen by mid-December and further erosion is retarded or prevented because of ice protection.

Erosion during 1971-72 took place between late November and late December which was characteristically the period of greatest storm activity and erosion. This location appears to be an "average" site since a small amount of erosion is normal during periods of combined high water and storm activity. There is no evidence to suggest that any local factors exert an influence over the processes operating at this site.

4. Profile Site 4.

The most abrupt and extreme changes have taken place at this site (Fig. 9). There was essentially no retreat of the dune bluff in the first year; however, considerable beach erosion occurred in the spring of 1971. Substantial erosion of the bluff (12 feet) occurred the following fall. The erosion in the spring of 1972 was tremendous; 30 feet of the bluff had eroded and 20 feet of the recession occurred during a single sampling interval. Although there was slight erosion at a few other locations during this period, the situation at this site was an isolated one.

Two factors may have contributed to the great amount of erosion. At the apex of Big Sable Point there is a vertical, steel wall protecting a U.S. Coast Guard installation and it is believed that the reflection and refraction of waves concentrate wave energy just to the south of this structure. The long fetch to the southwest also results in larger waves, which tend to increase the erosion.

The second important factor is that what was a wide protective beach had severely eroded during the spring of 1971. With little summer recovery, subsequent high energy periods during the following fall and spring enabled waves to directly attack the dune bluff.

5. Profile Site 5.

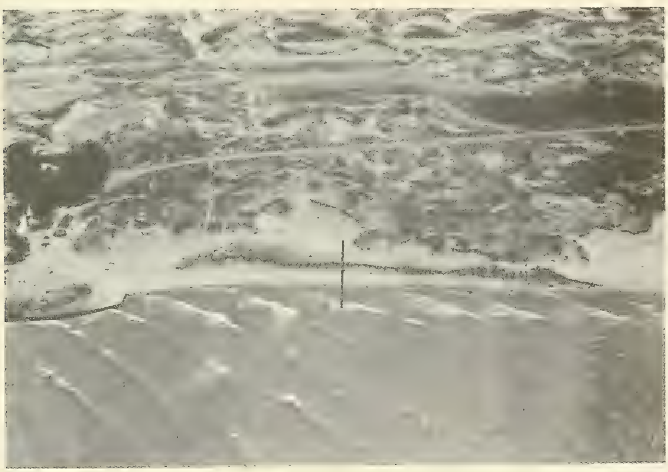
Nearly all of the terrace erosion at this site (Fig. 10) was during a 2-month period in the fall of 1970. Similar erosion did not take place at either of the adjacent sites during that period. Steep bluffs just to the north of the site were severely eroded throughout most of the study period. This site and site 10 with a similar shoreline orientation, were the only sites subjected to significant erosion during October and November 1970. This suggests a single storm was probably responsible for the erosion and had little effect at the other sites because of their different orientation to the wave approach.

Significant beach accretion occurred at site 5 in the spring of 1972; much sand was placed on what is normally a pebble and cobble beach. This

June 1970

Geomorphology. Beach at Big Sable Point has a shoreline orientation of N.7°E. This part of the eastern Lake Michigan coast is one of the most extensive dune areas. Dunes extend several miles in either direction from Big Sable Point and a few miles inland at the point. Dunes are covered with grass and small bushes. Virtually no gravel was found, reflecting the proximity to dunes.

Bench Mark Location (3 August 1970) (SW¼, NW¼, sec. 7, T.19 N., R.18 W.). About 300 yards, south of lighthouse at Big Sable Point, in front of blowout. Azimuths (from north): 7°48', lighthouse spire; 344°50', western margin of seawall; 358°12', U.S. Coast Guard flagpole. Bench mark was moved 15 feet landward 7 April 1972, and 50 feet landward 4 June 1972.



11 August 1971

Figure 9. Location and geomorphology of profile site 4.

June 1970

Geomorphology. Beach at Summit Township Park (Mason County) has a shoreline orientation of N.7°W. and is adjacent to bluffs of glacial drift. At times, glacial till was observed cropping out just lakeward of the plunge step. Foreshore comprised of well-sorted and rounded cobbles. Large percentage of the sand in backshore is from a sand terrace where the upper swash of waves has undercut the terrace and vertical slope has failed.

Bench Mark Location (3 August 1970) (NW¼, sec. 23, T.17 N., R.18 W.). Immediately fronting large, dead maple tree, just south of Summit Park. Azimuths (from north): 83°04', north of maple tree; 201°15', Little Sable Point; 343°19', end of groin; 351°39', large stump west edge.

11 August 1971

Figure 10. Location and geomorphology of profile site 5.

site is located in an area where net longshore transport is mixed (Fig. 5) so a change in the direction of longshore transport is not unexpected.

6. Profile Site 6.

This site (Fig. 11) showed no erosion to the adjacent dunes during the study period. However, there was a significant loss of beach sediment during the second year. The absence of dune erosion at this site can be attributed to the convergence of littoral transport and the associated abundance of beach sand in the area.

7. Profile Site 7.

During the first year this site (Fig. 12) experienced the most erosion of all 17 sites (Table 4); erosion was spread over all months with most occurring in November and December, a time of expected high wave energy. The 8 feet of erosion in late December and early January was unusual. Only one other site experienced erosion during each of those periods and it was a different site in each period.

Erosion was restricted to the November-December interval during the second year, a period when eight sites showed erosion.

8. Profile Site 8.

Although this site (Fig. 13) had no significant bluff erosion during the study period, a considerable amount of erosion occurred beginning about 100 yards south of the profile site. The beach was typically characterized by thick lag concentrates of heavy minerals, and there was some accretion during the second year.

The location of this site, adjacent to an area of shore protection, is probably a factor in its stability. The profile is about 100 feet south of a stretch of coast that has been stabilized by large blocks of concrete that protect the road adjacent to the lake. This stabilized zone extends for about one-quarter mile. Immediately north is a stream which serves as the outlet for Duck Lake. The beach is wide, shows no signs of erosion, and is partly sheltered by the concrete revetment. Storm waves are prevented from impinging on the beach but have considerable effect immediately to the south. The revetment also retards the normal southerly longshore transport.

9. Profile Site 9.

This site (Fig. 14) experienced moderate terrace erosion during the study period, receding 6 feet the spring of 1971 and 3 feet the following fall (Table 4). Other than site 7, this was the only site to experience more than 1 foot of recession during the spring of 1971. A possible reason for the recession was the narrow width of the beach which permitted a direct attack of low-intensity spring storms on the foredune terrace.

June 1970

Geomorphology. Shoreline orientation at Little Sable Point is N.7°E.; beach is just south of large, active dunes near Silver Lake. Immediately adjacent are moderately active small grass-covered dunes. Beach and immediate nearshore composed of sorted, medium sand throughout the year. During the winter this was the only location that did not have a snow cover on the beach at any time, reflecting the significance of wind activity in this general area.

Bench Mark Location (3 August 1970) (NE¼, SE¼, sec. 35, T.15 N., R.19 W.). Public access area about 200 yards north of lighthouse at Little Sable Point. Grassy dune 60 to 65 feet north of path. Azimuths (from north): 164°26', westernmost of group of three poplar trees (120'); 173°12', lighthouse spire; 357°06', west side of private beach sign.

11 August 1971

Figure 11. Location and geomorphology of profile site 6.

June 1970

Geomorphology. Shoreline at Claybanks Township Park in Oceana County trends N.18°W. This is one of the most extensive regions of glacial till bluffs along the eastern shore of Lake Michigan. At the base of the bluffs is a narrow terrace of sand which contains a small eolian ridge.

Bench Mark Location (3 August 1970) (NW¼, sec. 17, T.13 N., R.18 W.). About 100 yards south of southern path to beach at Claybanks Park. On grassy bank in front of steep till bluffs. Azimuths (from north): 162°30', point of land south toward Montague; 325°02', outermost of old piling in surf.

11 August 1971

Figure 12. Location and geomorphology of profile site 7.

Geomorphology. Dunes and Pleistocene lake sands characterize the beach. Shoreline orientation is N.24°W. Location is just south of a paved highway between Lake Michigan and Duck Lake. Recent erosion has endangered the highway and large concrete slabs have been dumped along the beach where the highway is close to the lake. Net littoral drift is to the south so that the site is in the lee of the protected beach and is deprived of sediment transported downdrift.

Bench Mark Location (3 August 1970) SE¼, NW¼, sec. 24, T.11 N., R.18 W.). West of Duck Lake on Scenic Drive just south of road about 150 feet. Azimuths (from north): 335°25', *No Parking* sign facing north; 345°10', *No Parking* sign facing south. Bench mark was moved 5 feet landward 24 October 1970.

May 1970

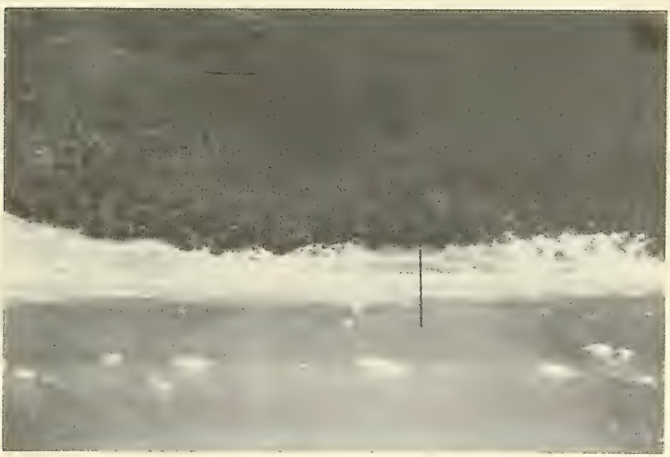
11 August 1971

Figure 13. Location and geomorphology of profile site 8.

June 1970

Geomorphology At P.J. Hoffmaster State Park in Muskegon County; shoreline orientation is N.25°W. Coastal morphology is comprised of large stabilized dunes with mature trees. Between dunes and beach is a broad foredune terrace which is grass-covered. Beach and nearshore zone are typically medium, well-sorted sand.

Bench Mark Location (3 August 1970) SW¼, sec. 25, T.9 N., R.17 W.). At P.J. Hoffmaster State Park on Lake Harbor Road south of Muskegon. About 300 yards south of beach access and 130 feet north of *Patrolled Beach* sign. Halfway between two large pine trees. Azimuths (from north): 165°40', power company smokestack; 167°00', west edge of red house on Grand Haven jetty; 331°04', red light tower, Muskegon jetty.



11 August 1971

Figure 14. Location and geomorphology of profile site 9.

Erosion in November-December 1971 was slight and was during the typical period of overall erosion. The beach at this site was not able to recover its original configuration during the second year (see App.).

10. Profile Site 10.

This site (Fig. 15) was severely eroded during the first year and experienced a modest amount of erosion the second year. All of the recession occurred in the fall. Although recession took place over a 4-month period in 1970, more than 60 percent was during a single sampling interval in October-November and was probably related to a single storm. Site 5 was the only other site to experience significant erosion during that period (both locations have the same shoreline orientation). Erosion during 1971 was 6 feet of bluff retreat and was spread uniformly over a 3-month period in the fall. Adjacent sites were essentially stable during the period of extreme erosion.

11. Profile Site 11.

The profile at site 11 (Fig. 16) remained stable throughout the first year of study and experienced only 4 feet of erosion during the fall storm period in the second year (Table 1). Closely spaced survey data are available from a time-series study conducted at this location during the summer of 1970 (Fox and Davis, 1971a, b; Davis and Fox, 1971).

At this site there are fetches of between 80 to 180 miles in directions from which strong winds are frequent (Fig. 2). These winds could produce waves large enough to cause modest recession rates. The terrace recession in late fall of 1971 was during the period of normal high energy. Site 12 to the south also showed significant erosion during the same period, suggesting a regional effect of storm activity. These two sites are the only adjacent locations that experienced "simultaneous" erosion during the entire 2-year period.

12. Profile Site 12.

Only 2 feet of terrace recession occurred at this site (Fig. 17) in the first year of study; however, there was 15 feet of erosion during a 2-month period the second year. The erosion occurred in early fall of 1970 when only two other sites experienced erosion; the following year erosion took place during the usual high-energy period just before ice cover. Although a number of sites were eroded during November-December 1971, this site and site 11 were the only two that experienced erosion during the succeeding 4-week period.

13. Profile Site 13.

Except for a 2-foot recession during late fall of 1971, this site (Fig. 18) was stable throughout the study period. This location has been monitored since June 1968 as part of another study (Davis, 1972), thus providing 4 years of profile data which cover a range of lake levels.

June 1970

Geomorphology. The public access beach at Buchanan Street (Ottawa County) has a shoreline orientation of N.11°W. and is located along a coast composed of small dunes covered with mature trees. These dunes extend to the active beach. Subsequent erosion has cut back to a till layer which rises about 8 feet above the lake and is capped by sand dunes

Bench Mark Location (3 August 1970) (cor. secs. 16, 17, 20, 21, T.7 N., R.16 W.). At public access on Buchanan Street south of Grand Haven. Profile is continuation of fence line at north side of right-of-way. Azimuths (from north): 15°25', flag-pole at first house; 174°23', radar dome at Saugatuck; 338°54', west edge of red house of Grand Haven jetty; 340°10', red lighthouse. Bench mark was moved 20 feet landward 20 November 1971.

11 August 1971

Figure 15. Location and geomorphology of profile site 10.

Geomorphology. Beach north of Holland, Michigan, has a shoreline orientation of N.3°E. Small stabilized dunes are bounded by a narrow foredune terrace which is grass-covered. Site is one of the profiles surveyed in a study of beach processes by Davis and Fox (1971) and Fox and Davis (1971b).

Bench Mark Location (3 August 1970) (NW¼, sec. 21, T.5 N., R.16 W.). In front of DeLeeuw residence, 396 north Lakeshore Drive, Holland; about ¼-mile south of Park Township Public Beach. Azimuths (from north): 183°33', red lighthouse, Holland; 187°45', end of jetty, Holland; 357°18', end of jetty, Port Sheldon.

June 1970

11 August 1971

Figure 16. Location and geomorphology of profile site 11.

Geomorphology. Public beach at Douglas, Michigan, has a shoreline orientation that trends N.16°E. Stabilized dunes are present with a typical foredune terrace covered by grass. High bluffs of glacial till a few miles to the south.

Bench Mark Location (3 August 1970) (SE¼, NW¼, sec. 17, T.3 N., R.16 W.). Douglas Village Public Beach, about 10 feet south of northern boundary of public beach on grassy bank. Azimuths (from north): 4°42', smokestack, Port Sheldon; 13°54', Saugatuck jetty, end; 45°30', northwest corner of glass-enclosed porch.

June 1970

11 August 1971

Figure 17. Location and geomorphology of profile site 12.

June 1970

Geomorphology. Site is located near Glenn, Michigan, where the shoreline trends N.15°E. Glacial till bluffs rise about 40 feet above lake level for several miles in both directions. Active beach abuts these till bluffs. A slight protuberance in the shoreline is present a few hundred yards south. Profile has been monitored since June 1968 (Davis, 1973b).

Bench Mark Location (3 August 1970) (NW cor., sec. 31, T.2 N., R.16 W.). Public access at Glenn below road on till bluff and 100 yards south of public access. In line with large oak tree on bluff crest. Azimuths (from north): 48°30', west edge of oak tree on top of bank; 99°32' center of large oak tree in line with profile. Bench mark was moved 5 feet lakeward 22 November 1970 and 10 feet landward 21 December 1971.

11 August 1971

Figure 18. Location and geomorphology of profile site 13.

Stability is based on local shoreline configuration and net longshore transport. There is a slight prominence in the shoreline configuration a few hundred feet south of the site. Since net transport is to the south (Fig. 5; Hulsey, 1962) it is possible that periods of general erosion causes littoral drift to accumulate at site 13 (Davis, 1972). This accretion protects the adjacent clay-till bluff from direct wave attack. Late fall storms erode the beach, rendering the bluffs more vulnerable to waves; the beach is rebuilt in spring and summer.

14. Profile Site 14.

Terrace erosion was completely stable at this site (Fig. 19) during the 2-year study period. This location, also monitored since June 1968, showed considerable erosion during 1968-70. More than 25 feet of beach eroded in late fall of 1968 and a small amount occurred during an unusually severe summer storm in 1969 (Fox and Davis, 1970b). Although the beach has exhibited changes, no erosion to the foredune area has occurred since 1969.

Beach width varies considerably but there is a general abundance of beach sediment as evidenced by the frequent presence of ridge and runnel topography. This protects the dunes from any direct wave attack and stabilizes the terrace. Although the study site remained stable, severe erosion was noted only a few hundred yards in either direction of the location.

15. Profile Site 15.

The bluff at this site (Fig. 20) is composed of clayey till and was essentially stable during the 2-year period (Table 4). There was some steepening of the bluff in both fall periods, resulting in some slumping during the subsequent spring thaw. The beach width also showed some stability with variation being less than that at most locations.

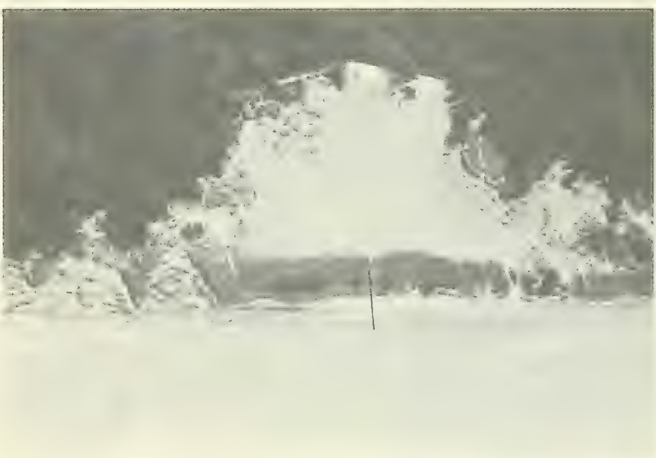
16. Profile Site 16.

This site (Fig. 21) was also stable with the exception of a few feet of erosion during the first study year. The bluff receded 4 feet in the late fall of 1970 and 1 foot the following spring. No erosion occurred during the second year. This site was investigated in great detail during a time-series study in the summer of 1969 (Fox and Davis, 1970a). Most of the bluff erosion took place during a severe summer storm (Fox and Davis, 1970b) and the fall storm period. Total recession during the last half of 1969 was 25 feet. Stability has prevailed since that time, however, despite the high energy conditions that occurred in the fall of 1970 and 1971. Erosion was pronounced in adjacent areas during both years.

June 1970

Geomorphology. The Van Buren State Park site is located at the base of a large blowout in vegetated dunes that rise about 150 feet above lake level and are among the largest along the eastern Lake Michigan coast. Shoreline orientation is N.25°E. Top of a thick Pleistocene peat bed, exposed in a steeply inclined terrace at the upper margin of the beach, has been dated at 4,000 B.P. (Zumberge and Potzer, 1956). During a 1969 summer storm, glacial till was exposed in the nearshore zone just lakeward of the plunge step; not known to be exposed during the present study.

Bench Mark Location (3 August 1970) (NW¼, SE¼, sec. 32, T.1 S., R.17 W.). At Van Buren State Park. About ½-mile north of beach access in front of large blowout. Just south of path leading up to blowout. Azimuths (from north): 13°10', red lighthouse on south Haven jetty; 14°51', east end of catwalk on south Haven jetty; 108°55', northernmost dead tree in group of four or five.



11 August 1971

Figure 19. Location and geomorphology of profile site 14.

June 1970

Geomorphology. Site has a shoreline orientation of N.34°E. Profile is adjacent to bluffs of glacial till at the Hagar Township Park (Berrien County). Bluffs rise about 35 feet above the lake and continue for 1 mile or more in either direction. Bluffs are probably stable as they are covered with fairly mature trees and shrubs.

Bench Mark Location (3 August 1970) (SE¼, NW¼, sec. 15, T.3 S., R.18 W.). At Township Park north of Lake Michigan Beach on Blue Star Highway, 152.5 feet south of steps on clay till bluff. Azimuth (from north): 32°55', corner of concrete wall. Bench mark was moved 15 feet landward 8 April 1972.

11 August 1971

Figure 20. Location and geomorphology of profile site 15.

June 1970

Geomorphology. Beach at Stevensville, Michigan, has a shoreline orientation of N.28°E. and is the site of the time-series study by Fox and Davis (1970a, b). Foredune terrace is adjacent to small vegetated dunes. One mile or more to the north (updrift) is an extensive stretch of high bluffs of glacial till.

Bench Mark Location (3 August 1970) (NW cor., sec. 20, T.5 N., R.19 W.). About ¼-mile north of village of Chalet-on-the-Lake. Just south of second house in village on grassy bank. Azimuths (from north): 96°50', television antenna just behind dune crest; 206°40', western peak of westernmost part of village.

11 August 1971

Figure 21. Location and geomorphology of profile site 16.

17. Profile Site 17.

The sand terrace at this site (Fig. 22) was subjected to only 3 feet of erosion the first year and 10 feet the second year. The erosion occurred during the fall storm period with a small amount in late spring of 1972. The beach is generally uniformly sloping and moderately wide. There is a sand shortage in the inner nearshore area as evidenced by incomplete ripples over a clay-till bottom (Davis, 1964). In addition, water depth increases rapidly just beyond the plunge step.

Erosion is largely the result of the general scarcity of sand which inhibits beach and longshore bar growth, permitting more wave energy to be imparted on the beach and sand terrace. Erosion in the second year is unrepresentative because the profile is near a large tree on the terrace which stabilized the terrace locally although more erosion occurred a few tens of feet in either direction.

VI. BEACH SEDIMENT CHARACTERISTICS

The sediment characteristics for the profile sites and the range of the sand sizes during the 2-year study are presented in Table 5.

Beach sediments along eastern Lake Michigan are characterized by wide ranges in textural character. Pebbles and cobbles are commonly scattered or accumulated in narrow bands along the sand beaches. Size analyses were made of the sand fraction only, and size data in this section refer only to the sand fraction of a beach sample that might include a significant amount of pebbles. Sand-size analysis consisted of computation (using the RSA curve) of the mean, and the sorting and skewness of each sediment sample by the graphic method (Folk, 1968). Mean is a measure of average size; sorting refers to the uniformity of the sediment size; and skewness measures the degree and direction of asymmetry.

In general, beach sands of eastern Lake Michigan are well sorted, positively skewed, and medium-coarse, with backshore sands generally finer and more sorted than foreshore sands. Nearly all samples collected have a mean grain size between 0.330 and 0.189 millimeters (1.60 and 2.40 phi), although a few coarser sand samples occurred at sites 13 and 17 where gravel is common. Coarse beach sands are typically adjacent to nearby bluffs of glacial drift, i.e., sites 5, 12, 13, 15, and 17, and the finest grain size is located on beaches adjacent to dune areas at Big Sable Point (site 4) and Little Sable Point (site 6). Most beach sands are well sorted with values between 0.20 and 0.25 phi units (Folk, 1968). Coarser sands are generally less sorted than fine sands. Nearly all samples were fine-skewed (0.00 to +0.30) with a few strongly fine-skewed and slightly coarse-skewed types as exceptions.

VII. VARIABLES AFFECTING PROFILE CHANGES

The total bluff and terrace erosion for all 17 sites are shown by a histogram (Fig. 23), with each year plotted separately. The total

June 1970

Geomorphology. Site located at Chickaming Township Beach, Lakeside, Michigan, has a shoreline orientation of N.43°E. Coastal area is dominated by stabilized dunes and bluffs of glacial till. Till is exposed on a bluff just to the north and behind the site. In an earlier study (Davis, 1964) glacial till was exposed in the inner nearshore area, but was not observed during this study. Sand terrace is present in most of the area.

Bench Mark Location (3 August 1970) (Sec. 19, T.7 S., R.2 W.). Public beach at Lakeside. About 125 feet north of steps on grassy bank on front of till bluff. Azimuths (from north): 227°40', post of south side of steps; 232°35', western side of northern post. Bench mark was moved 10 feet landward 21 December 1971 and 15 feet landward 8 April 1972.

11 August 1971

Figure 22. Location and geomorphology of profile site 17.

Table 5. Sediment characteristics.

Profile site	Description	Sand-size range (mm)	Sand-size range (ϕ units)
1	Backshore sand; foreshore pebbles and cobbles	0.401 to 0.250	1.32 to 2.00
2	Sand; heavy minerals sometimes present	0.330 to 0.241	1.60 to 2.05
3	Sand; scattered gravel sometimes in surf zone	0.914 to 0.245	0.13 to 2.03
4	Sand; heavy minerals sometimes present	0.293 to 0.210	1.77 to 2.25
5	Mostly cobbles; some sand on backshore	0.536 to 0.238	0.90 to 2.07
6	Sand	0.279 to 0.195	1.84 to 2.36
7	Gravel and sand; heavy minerals rare	0.281 to 0.206	1.83 to 2.28
8	Thick, heavy mineral concentrates; gravel rare	0.371 to 0.210	1.43 to 2.25
9	Sand; some pebbles in surf zone	0.287 to 0.203	1.80 to 2.30
10	Sand; pebbles occasionally in narrow zone along upper foreshore; heavy minerals common	0.312 to 0.215	1.68 to 2.22
11	Sand; few pebbles in surf zone	0.323 to 0.225	1.63 to 2.15
12	Sand; bands and cusps of gravel	1.110 to 0.210	-0.15 to 2.25
13	Sand, gravel, and pebbles common in foreshore; clay present	0.747 to 0.233	0.42 to 2.10
14	Sand; some gravel and pebbles	0.272 to 0.207	1.88 to 2.27
15	Sand; narrow zones of gravel	0.314 to 0.202	1.67 to 2.31
16	Sand; bands of gravel and granules	0.642 to 0.206	0.64 to 2.28
17	Sand and fine gravel	0.959 to 0.195	0.06 to 2.36

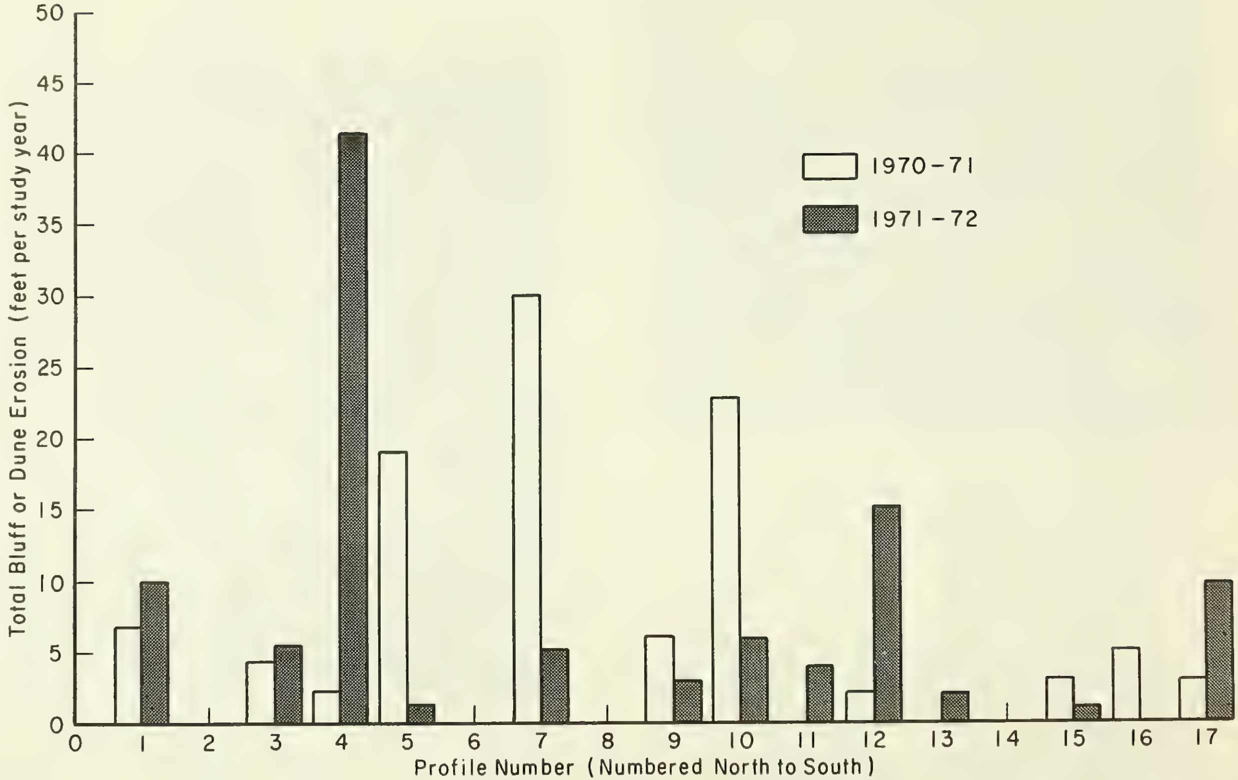


Figure 23. Geographic variation in erosion, eastern shore of Lake Michigan. Total bluff or dune erosion shown by year at each profile.

landward bluff or dune recession for all sites by month and by year are shown in Figure 24.

1. Lake Level and Seasonal Effects.

Changes observed during the 2 years of systematic monitoring of the 17 sites are assumed to be related to changes in lake level and seasonal weather conditions.

Mean annual lake level began to rise in 1965 (Fig. 3), and it had risen about 4 feet by 1973. One author observed that, during periods of low lake level (1963-64), there was considerable beach accretion and a high berm developed with an overall large beach width. As lake level began to rise during 1965, the accreting beach profile was slowly changed to an eroding beach profile. The well-developed berm was removed and beaches were eroded to a generally narrow width. These changes were the combined result of a volume of sediment being removed from the beach by wave action, and the drowning of the subaerial beach due to a rise in lake level.

Although this condition has prevailed for the past few years there are times, during periods of low wave energy, when certain locations experience temporary beach accretion, and an accretionary profile forms. In the study period this was most prevalent at Little Sable Point (site 6). This site was the focus of converging longshore transport (Fig. 5) so sediment was available. However, during the second year this site was subjected to significant beach erosion. Although apparently not a place of littoral convergence, there was considerable beach accretion at site 5 during the second year of the study. Brief periods of beach accretion were also observed at other locations, but did not exceed one or two sampling periods.

The combination of high lake level and narrow beaches without berms has provided easy access, by waves, to the foredune terrace or bluffs. All of the sites exhibit a pattern of erosion that can be related to seasonal weather changes. There is an increase in overall erosion during the fall months with the maximum rate of erosion occurring just before winter ice cover. A period of less intense erosion follows ice breakup in the spring. Summer is relatively free of coastal erosion. However, this pattern does not conform to lake level cycles since the erosion rate is highest in November and December (Fig. 24) when lake level is approaching its lowest level within the annual cycle (Fig. 4). Lake level varies about 1 foot during the year due to seasonal changes in precipitation and runoff.

On an annual basis lake level and bluff or dune erosion could be related, as reported by Seibel (1972). During 1971-72, when lake levels were higher than in corresponding months of 1970-71, sites 1, 3, 4, 11, 12, 13, and 17 showed a greater amount of erosion (Fig. 23). However, sites 5, 7, 9, 10, 15, and 16 showed less erosion the second year, while

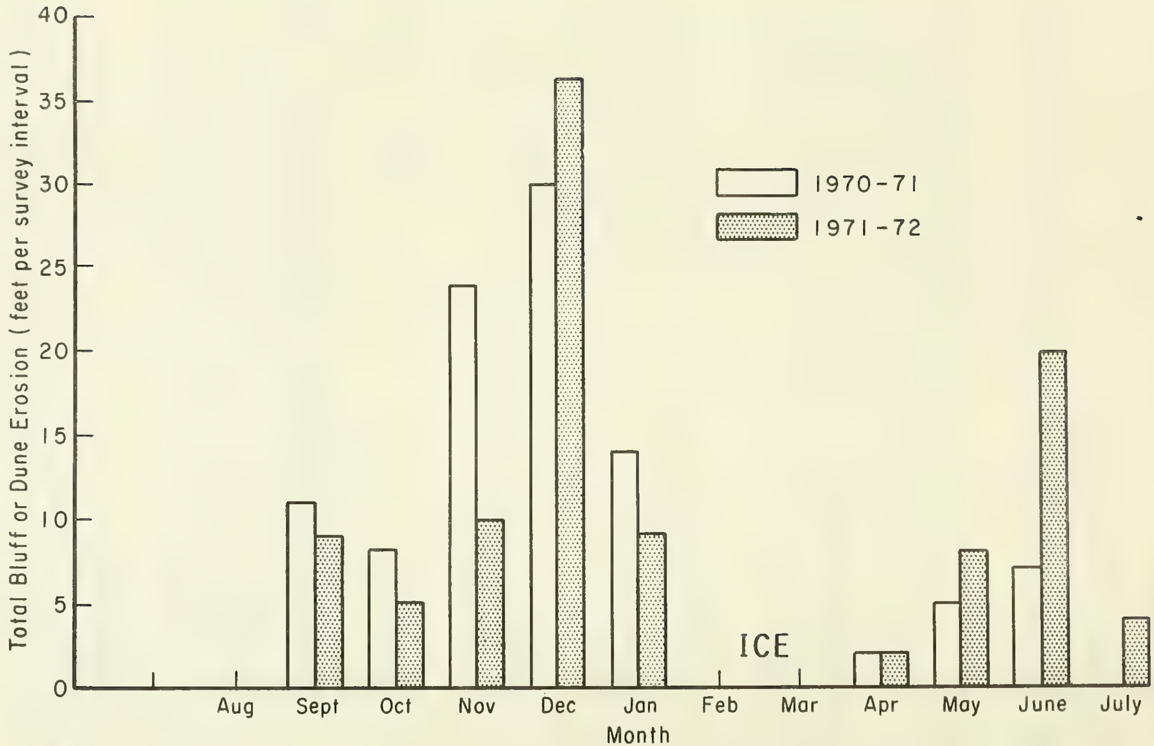


Figure 24. Seasonal variation in erosion, eastern shore of Lake Michigan. Total amount of bluff or dune erosion at all sites shown for each 4-week interval.

sites 2, 6, 8, and 14 showed little or no erosion during either year. Total retreat of the dunes or bluffs for all 17 sites was 104 feet the first year and 113 feet the second year.

2. Geographic Effects.

The 17 profile sites are located along a 250-mile segment of shore, at an average spacing of 15 miles. If the geographic distributions of bluff or dune erosion are considered, no patterns are apparent. No single profile site experienced erosion exceeding 10 feet during both study years (Fig. 23), and no two adjacent sites showed erosion exceeding 10 feet during the same year. This lack of correlation between profile changes at adjacent sites is surprising, especially in coastal regions where the shoreline orientation and beach morphology are similar.

The shoreline orientation ranges from N.25°W. (site 9) to N.43°E. (site 17); however, the majority of sites are oriented nearly north-south or slightly to the northeast (Table 4). Storms which generate destructive large waves move in a west-to-east pattern; the low pressure centers shift from a northerly latitude in summer to a southerly latitude in winter. As a result the wind direction and the approach of waves may vary along the entire coast of the lake. Wind intensity, fetch, and wave height may also vary. However, these parameters are not expected to differ significantly in a climatic sense at adjacent sites for a few tens of miles. Nearshore refraction can introduce local differences, but has not been studied.

3. Coastal Composition and Morphology.

There are either dunes, foredune terraces of loose sand, or bluffs of unlithified sediment behind the beaches. Some dunes are grass-covered and somewhat mobile; others are stabilized by mature vegetation. Bluffs are composed of both sorted sand and clay till. Susceptibility to erosion should be greater at profiles where the bluffs are composed of sand rather than till. Till is adjacent to the beach at sites 13, 15, and 17; the average erosion per year is 3 feet, compared to an average of 6.8 feet per year at the remaining sites.

4. Human Influence.

For most profiles manmade effects could be eliminated as a cause of erosion. An effort was made to keep sites away from jetties, groins, or other similar structures. There are two locations that are slightly affected by protective features which parallel the coast. At site 4 a vertical metal wall several hundred feet north of the profile protects the U.S. Coast Guard installation at Big Sable Point. At site 8 a large quantity of concrete slabs, beginning about 100 feet north, have been dumped along the shore to protect the highway.

5. Longshore Bars.

The significant variables may be the number, position, and geometry of longshore sandbars. These sandbars may be important in limiting the amount of wave energy reaching the beach by causing waves to break farther offshore, or by affecting the refracted direction of the waves near shore. However, longshore sandbars may explain some of the apparent randomness in time and location of bluff recession.

VIII. VOLUME, WIDTH, AND SLOPE DATA

1. Estimated Volumes of Erosion.

The volume of material removed from the dunes or bluffs was estimated during each year of the 2-year study. These values were computed by overlaying the first and last surveys for a study year, locating the intersection of the beach with the bluff on the first survey, dropping a vertical line from that intersection to the profile of the last survey, and then calculating the volume eroded landward of that vertical line. The resulting volume is shown two-dimensionally in Figure 25. The composition of the bluff (sand or till) and the volume eroded for each year are shown in Table 6. The pattern of erosion is presented in Section V, Profile Descriptions; volumes calculated range from 0 to 19.9 cubic yards per foot of beach front per year. Data on the size distribution of eroded material were not collected.

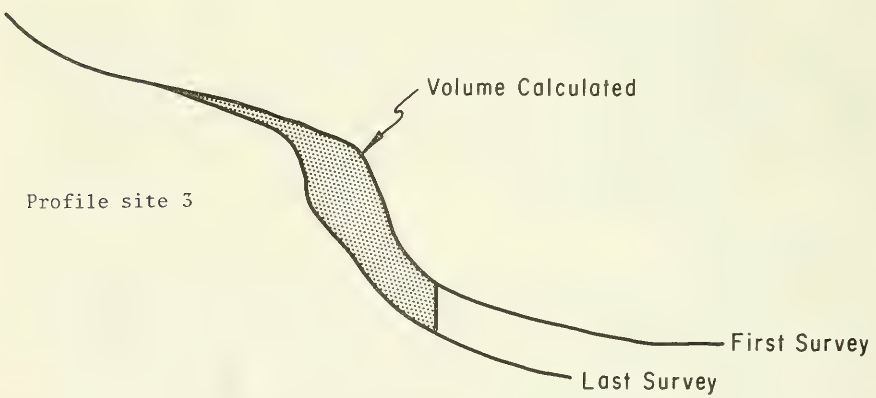


Figure 25. Example of eroded volume computation.

Table 6. Composition and volume of material eroded from terrace and bluff.

Profile	Composition	Volume of sand or till eroded[1] Aug. 1970 to July 1971	Volume of sand or till eroded[1] Aug. 1971 to July 1972
1	Sand	0.0	5.9
2	Sand	0.0	0.0
3	Sand	1.9	2.2
4	Sand	1.6	19.9
5	Sand	5.3	0.0
6	Sand	0.0	0.0
7	Sand and till	6.7	1.8
8	Sand	0.5	0.7
9	Sand	1.1	1.9
10	Sand and till	5.6	7.2
11	Sand	0.0	0.7
12	Sand	1.4	4.0
13	Till	0.0	0.0
14	Sand	0.0	0.0
15	Till	0.0	3.3
16	Sand	1.1	0.0
17	Sand and till	0.0	4.0

1. Cubic yards per foot of beach front.

2. Beach Width.

Beach width is defined as the distance from the waterline at the time of the survey to the base of the dune or bluff. Data limitations, described in Section IV, do not allow a precise estimate of beach width. The difficulty lies in determination of the beach-water intersection. A small vertical error in the measured profile results in a horizontal error of up to 30 times as large; vertical errors of up to 1 foot can be expected from the survey method by Emery (1961). In consideration of these potential inaccuracies, the beach widths were measured on the plotted profile using a lake level computed during the survey or from water level gage records at Holland, Michigan. The measured beach width showed a systematic seasonal variation. On an annual basis, width is at a minimum during the summer months, when lake levels are highest, increases through the fall, remains steady through the ice season and then decreases as lake levels rise in the spring. The data also reflect the higher lake levels during the second year of the study; the mean width for the second year is less than the width for the first year by approximately 5 feet.

3. Sediment-Slope Relationships.

No textural patterns in the beach sediment samples prevail along a major part of the study area, although each location is characterized by a particular sediment type which is retained throughout seasonal changes. In previous investigations of ocean beaches (Bascom, 1951; Shepard, 1963) it was found that the slope of the foreshore was directly related to the mean grain size and inversely proportional to wave height. However, Great Lakes data show no trend, only a wide scatter of points (Hulsey, 1962; Coleman, 1969). The center of these points is consistent with the tendency of steeper slopes occurring with lower wave climate.

A representative grain size-slope plot for site 10 is shown in Figure 26. The center of the scatter, excluding the backshore points, is at approximately 0.25 millimeters (2 phi) and $\tan \Theta = 0.111$; this point falls above the ocean beach curves of grain size-foreshore slope (compare Fig. 26 with Fig. 4-32 of the Shore Protection Manual, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1973).

IX. SUMMARY

An analysis of the profile and sediment data from 17 sites along eastern Lake Michigan suggest the following:

(a) Mean monthly values of bluff erosion, beach width, breaker height, wind, and lake level are given in Figure 27. In this 2-year period, lake levels were rising from a mean annual value of 578.93 feet above mean water line (MWL) in 1970 to 579.66 feet MWL in 1972. The rise resulted in narrow beaches without berms and easy access, by waves, to the foredune

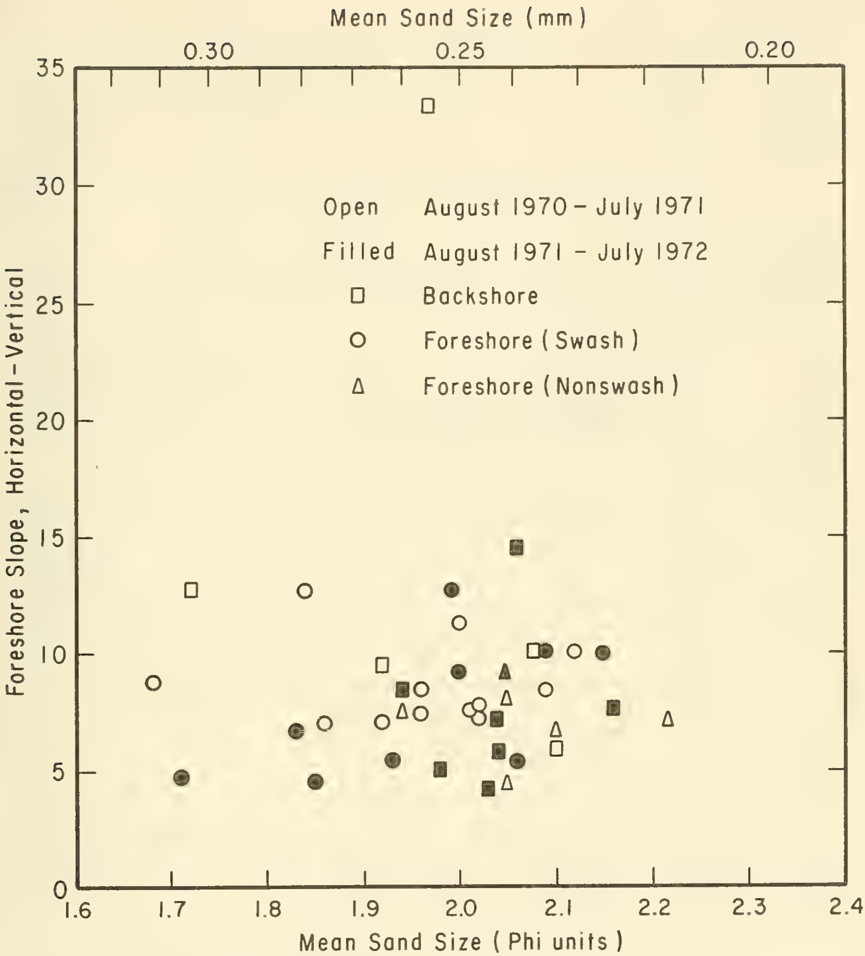


Figure 26. Foreshore slope versus mean sand size at profile site 10.

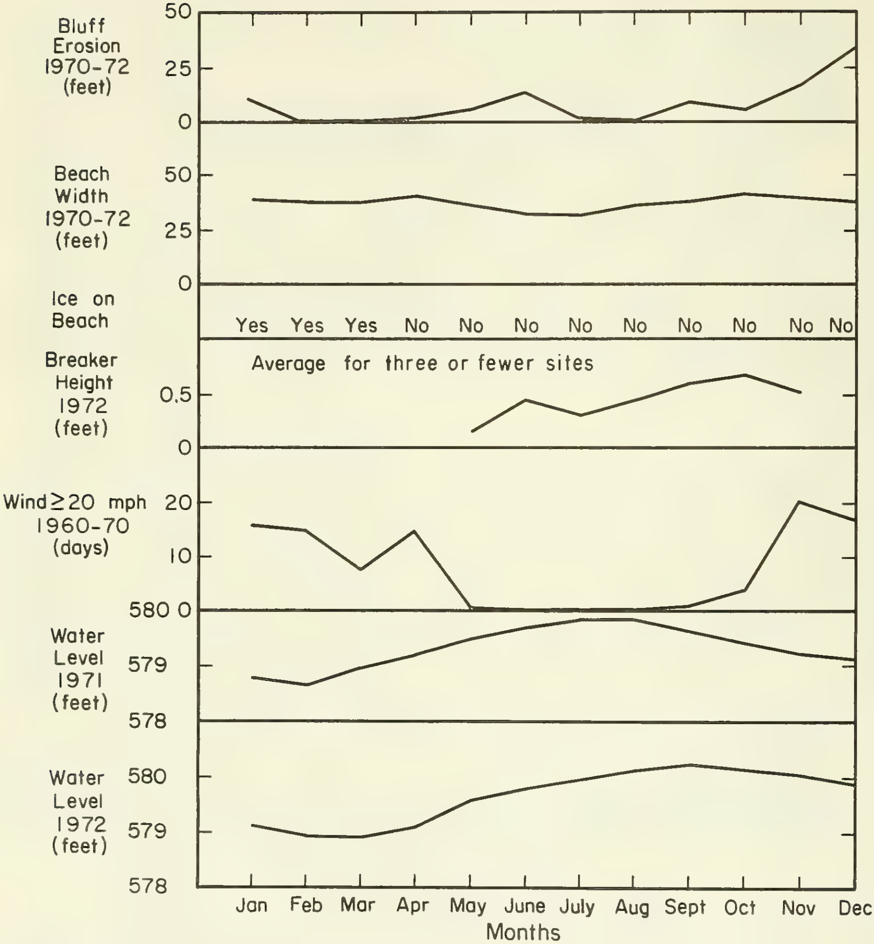


Figure 27. Mean monthly values of Lake Michigan environmental variables (wind data from Seibel, 1972).

terraces or bluffs. During this interval, 13 of the 17 profiles exhibited recession of the terrace or bluff while there was no change at the other 4 profiles. The amount of terrace or bluff erosion at each profile site for each 4-week period is summarized in Table 4. A histogram of the annual bluff or terrace erosion found at the various sites is presented in Figure 28. The average rate of recession of the terrace or bluff for all 17 sites was 6.1 feet the first year and 6.6 feet the second year.

(b) Changes at adjacent profiles were not usually correlated (Fig. 6). Adjacent profiles did not experience erosion over 10 feet in the same year. In several cases significant changes occurred only a few hundred yards from relatively stable profiles along straight stretches of beach. Wave climate does not usually vary greatly over distances tens of miles long, although refraction may change the direction of the waves. The position of longshore bars which may protect the backing beach is suggested as an explanation for the observed geographic variation in erosion.

(c) The recession of the dune or bluff, used as a measure of erosion at the profiles, varied with season and composition of the coastal sediment, but showed no clear-cut dependence on lake level. Most erosion occurred during the fall when storms were frequent (Figs. 2 and 24). After shore ice formed, the beach was protected until spring when erosion resumed at a reduced level. While previous investigators found a direct relationship between rate of erosion and lake level over a period of 50 years, this 2-year study showed that the total bluff erosion at all 17 sites was only slightly higher the second year, when lake levels were higher an average of 0.25 feet; only 7 of 17 profiles showed an increase during the second year. Bluffs composed of till eroded at only one-half the rate of predominantly sand bluffs or dunes (Table 6).

(d) Lake level was found to be related to beach morphology both on an annual basis, and over the 2-year study. Beaches were narrowest in early summer, when the lake level was at a maximum and widest in late fall. Beach width was less the second year, when the lake level was higher.

(e) Beaches in the study area are composed of sand, with varying amounts of gravel and cobbles, usually in bands. Concentrations of heavy minerals occurred frequently, indicating recent erosion. The beach sands are well sorted with a mean grain size between 0.189 to 0.330 millimeters (2.40 and 1.60 phi units). Plots of mean grain size versus foreshore slope (Fig. 26) show wide scatter, which is similar to findings by other investigators.

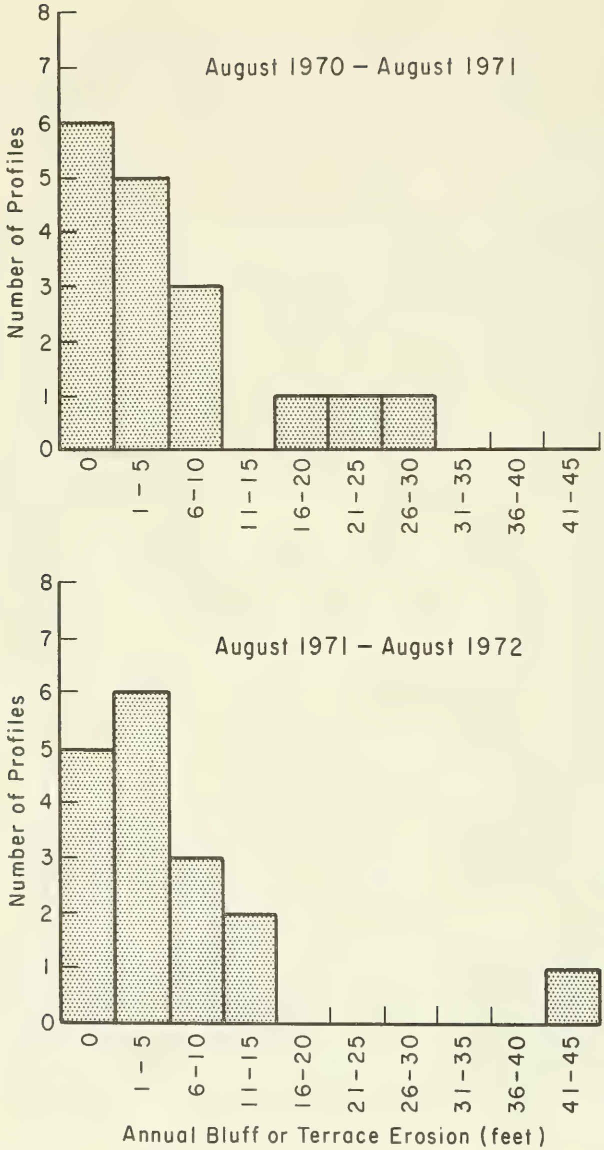


Figure 28. Distribution of yearly erosion.

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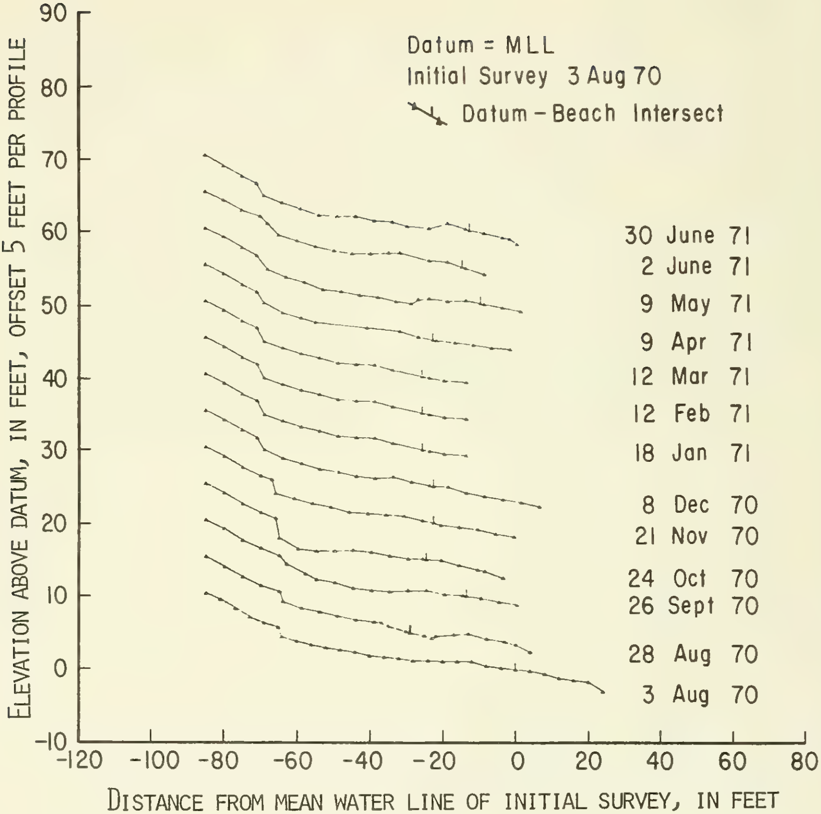
APPENDIX

Plotted profiles, August 1970 - July 1972,

for Sites 1 through 17, Eastern Lake Michigan



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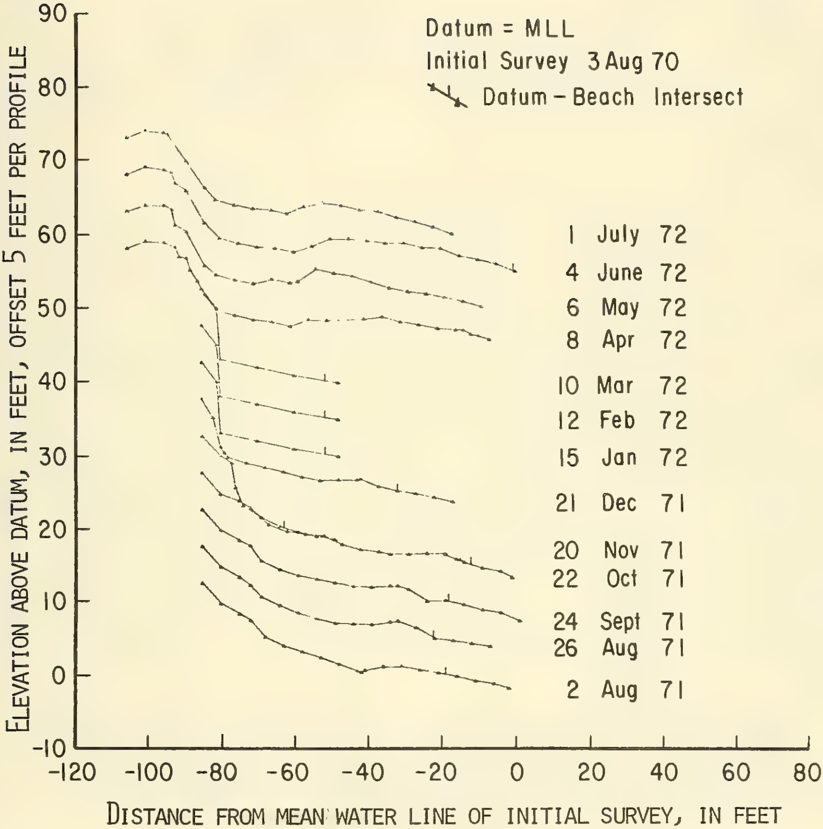

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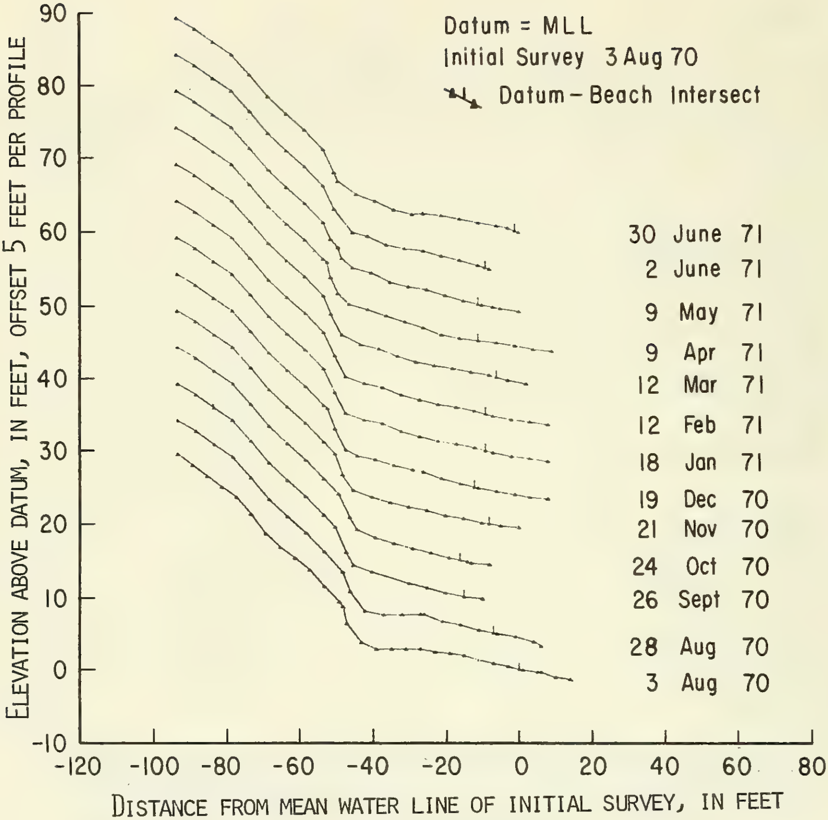

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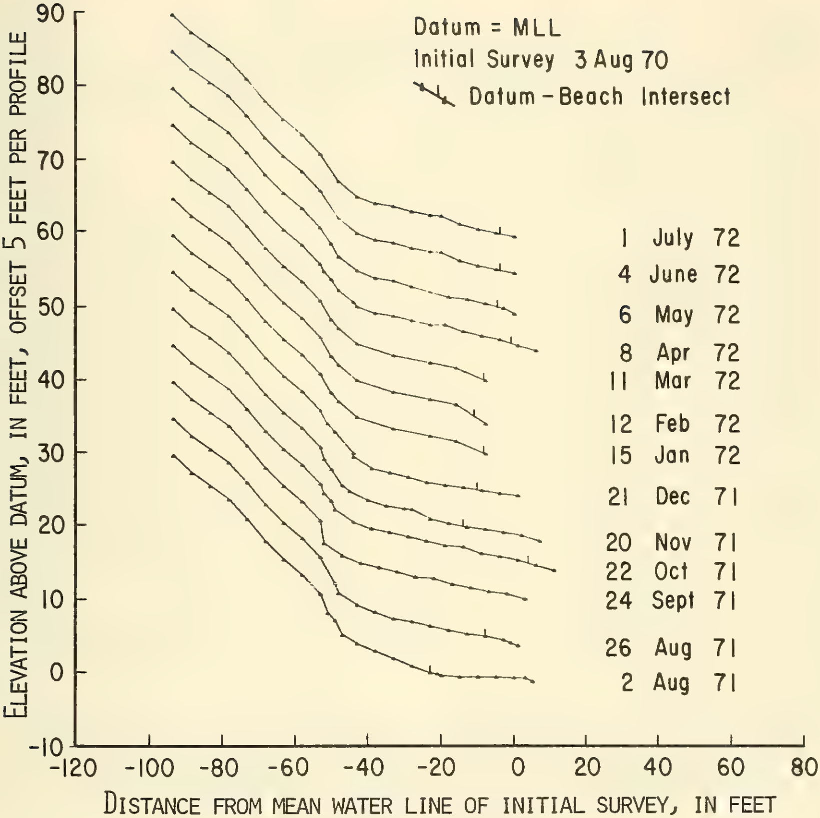

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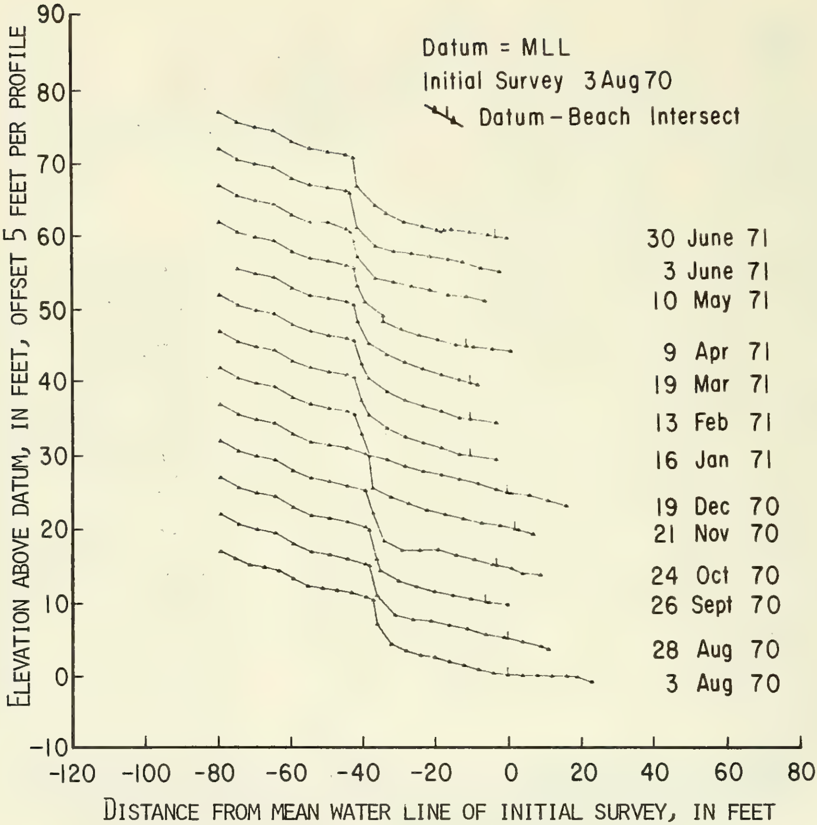

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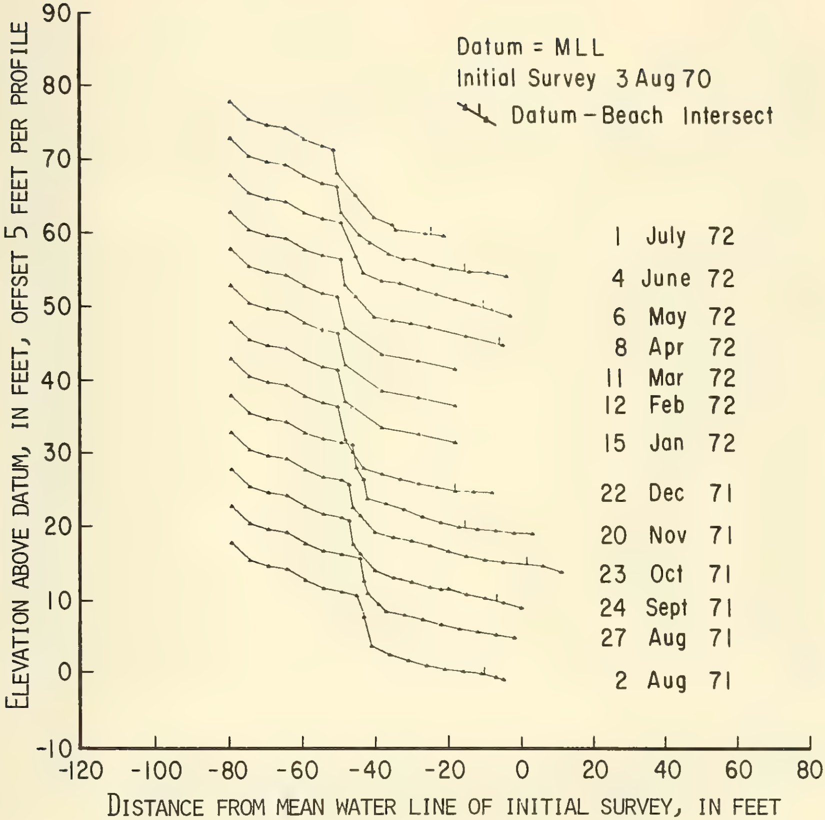

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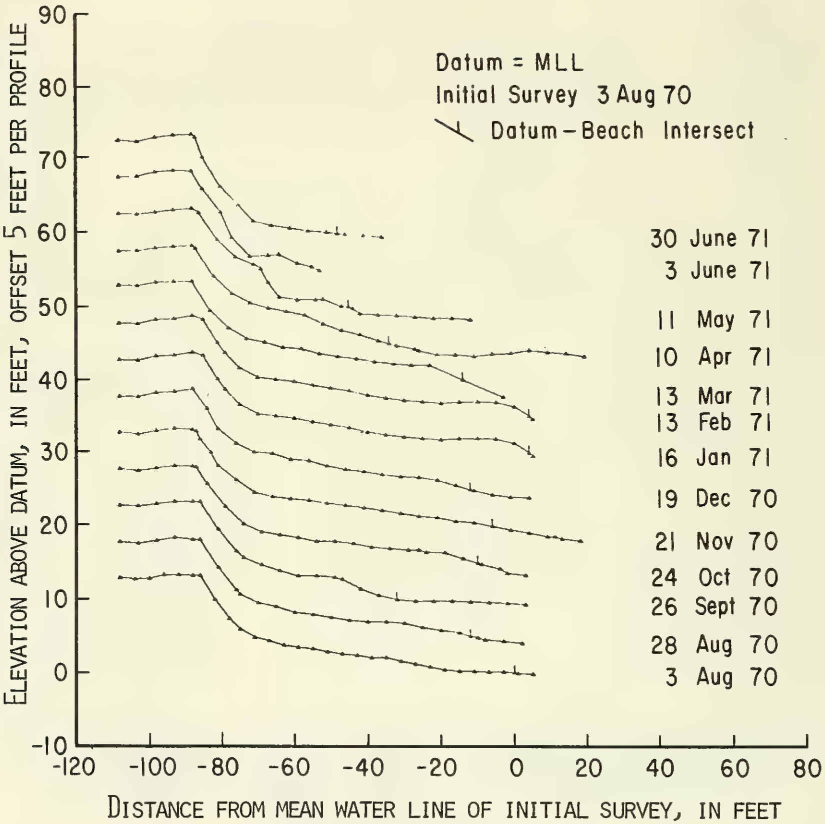

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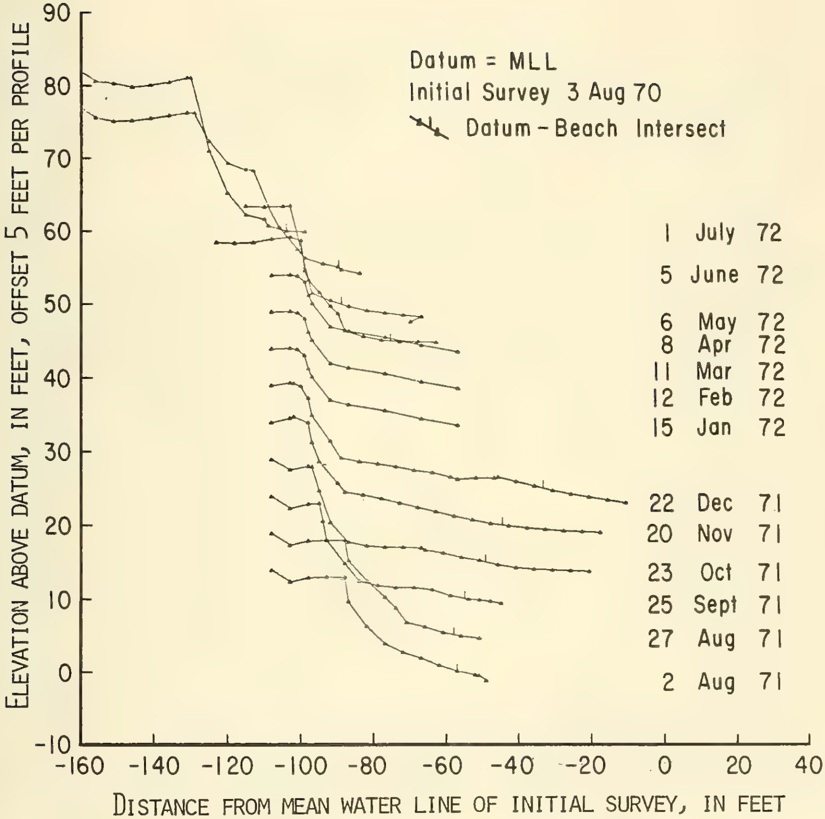

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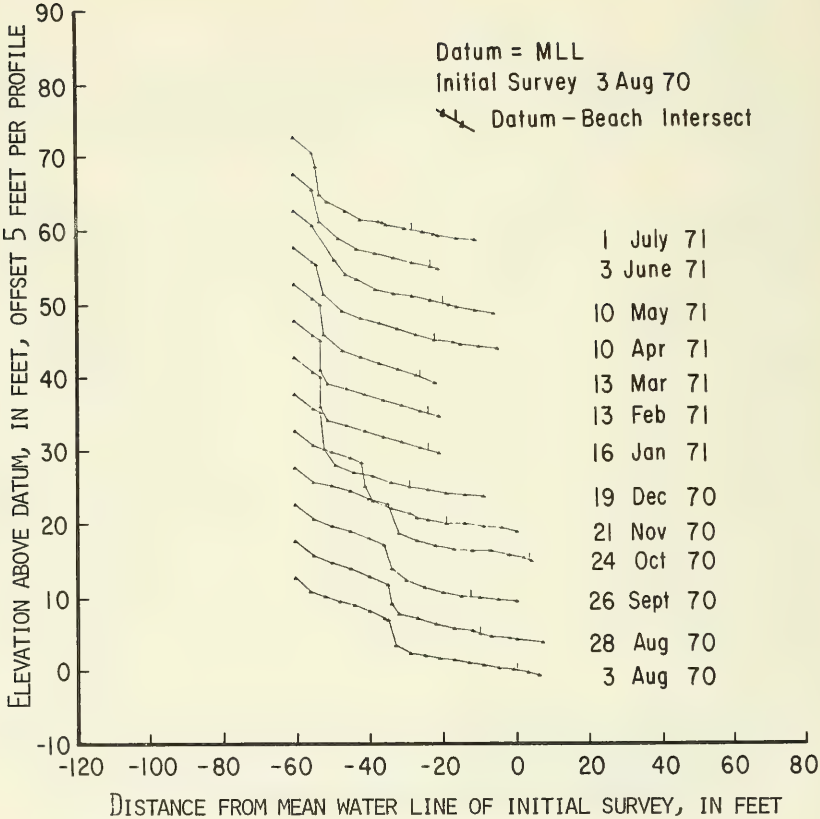

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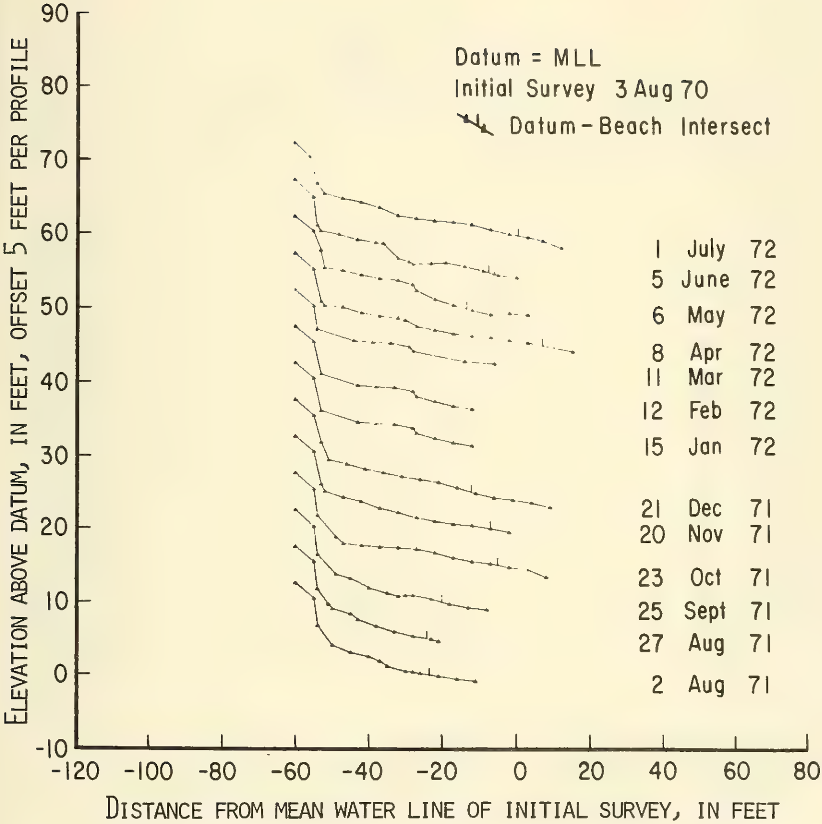

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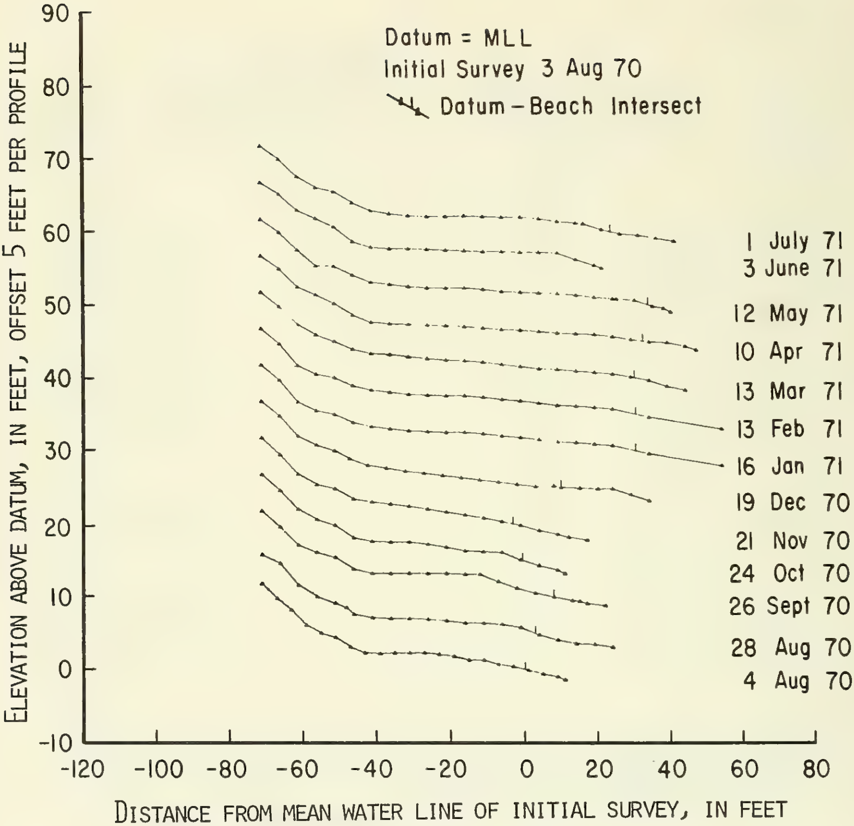

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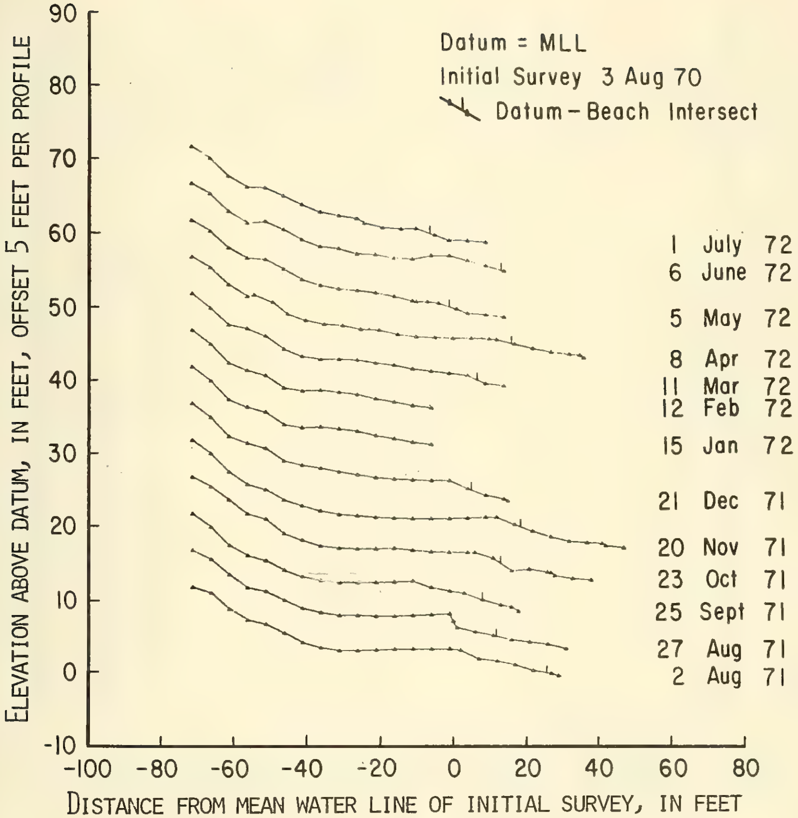

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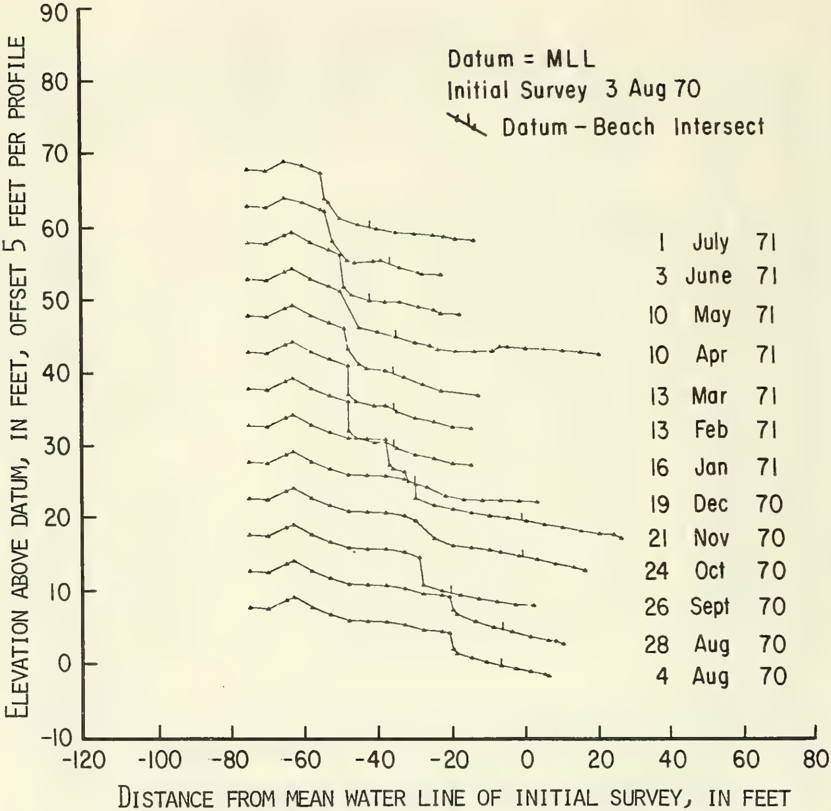

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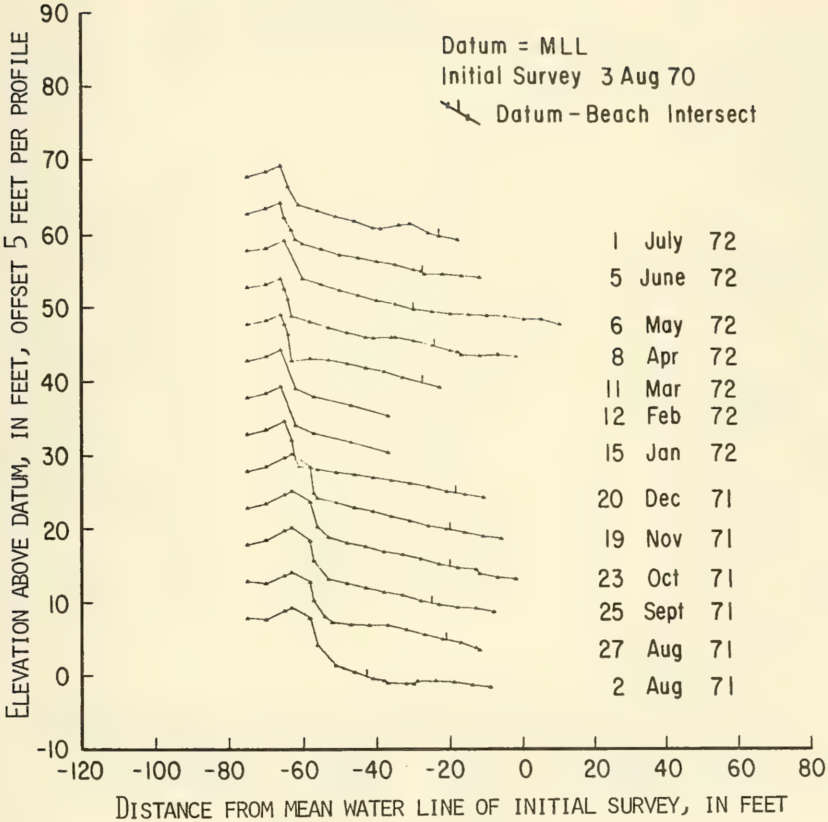

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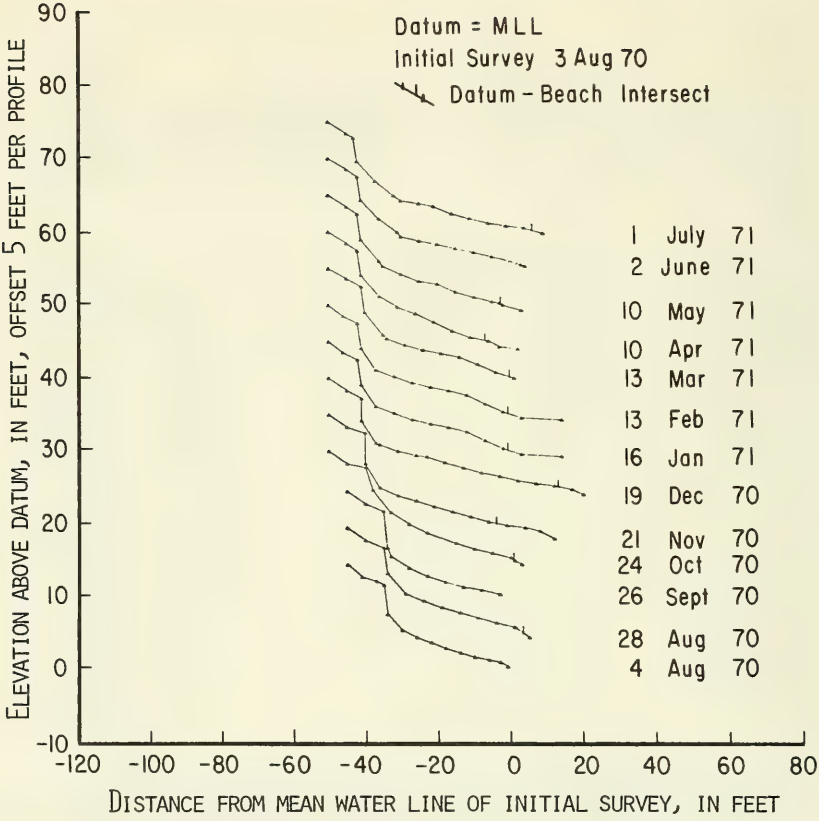

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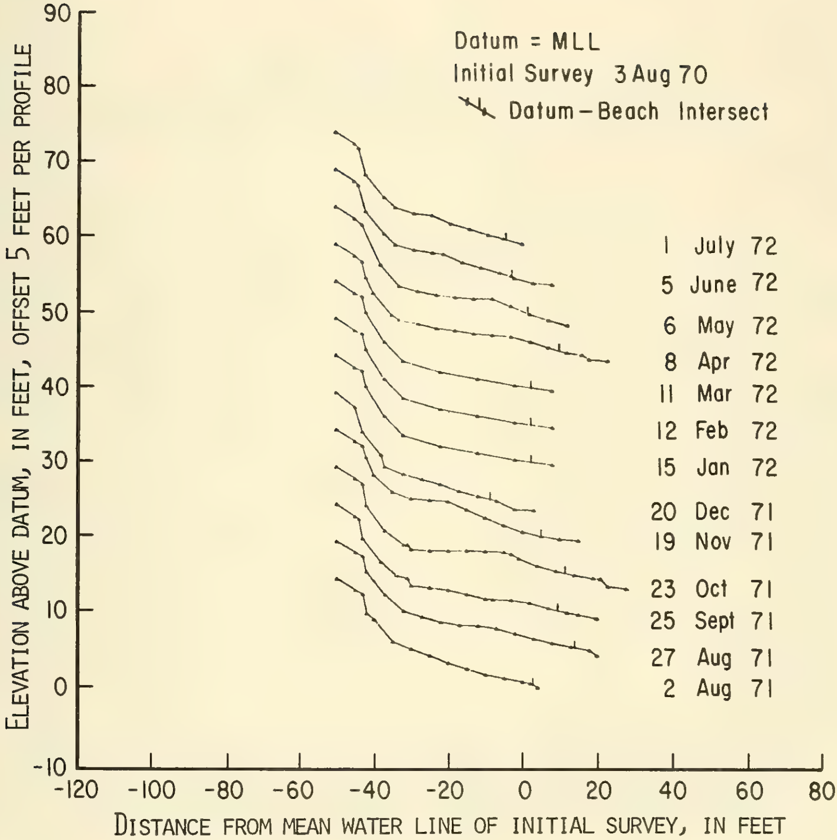

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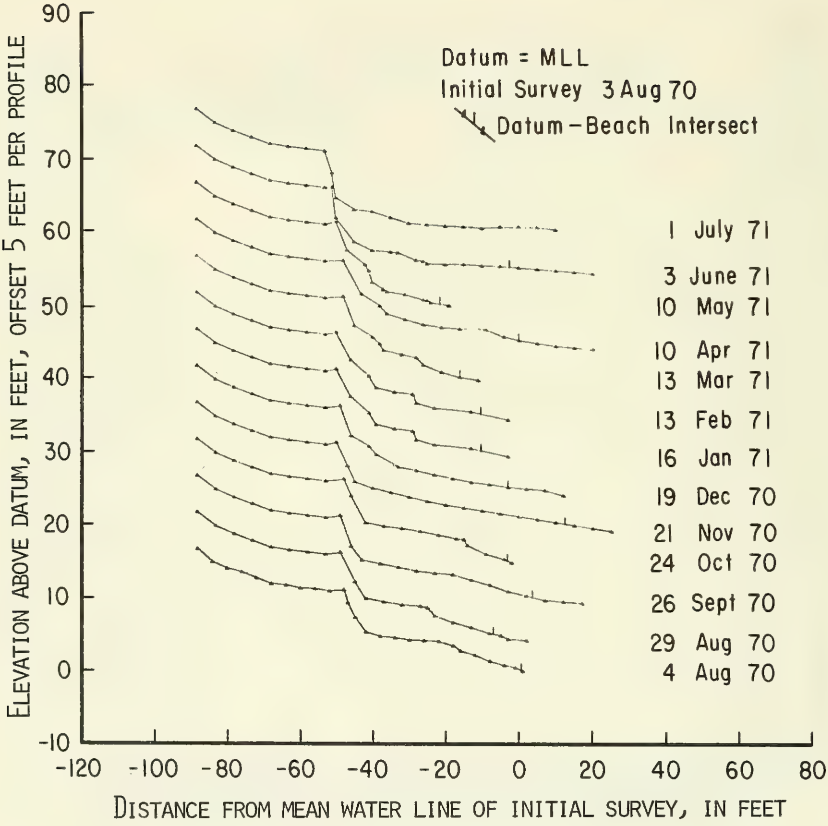

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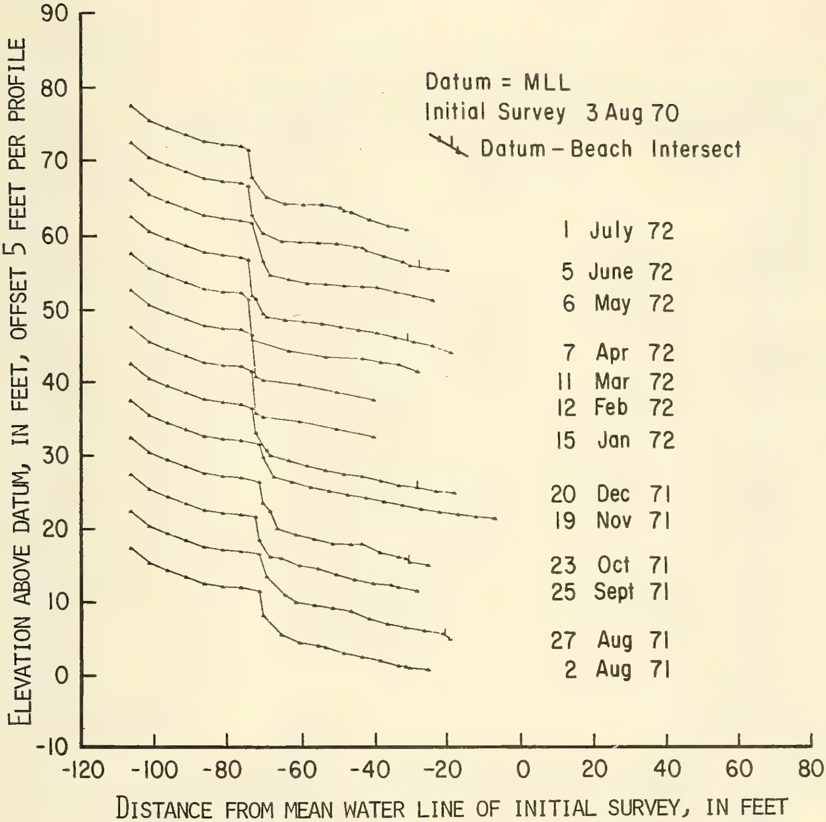

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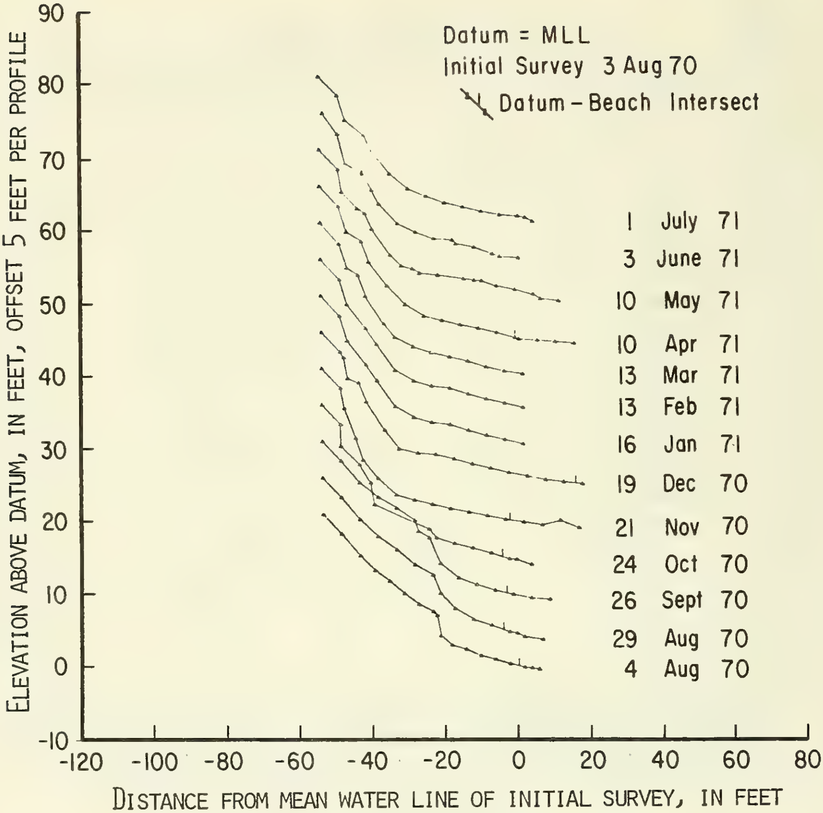

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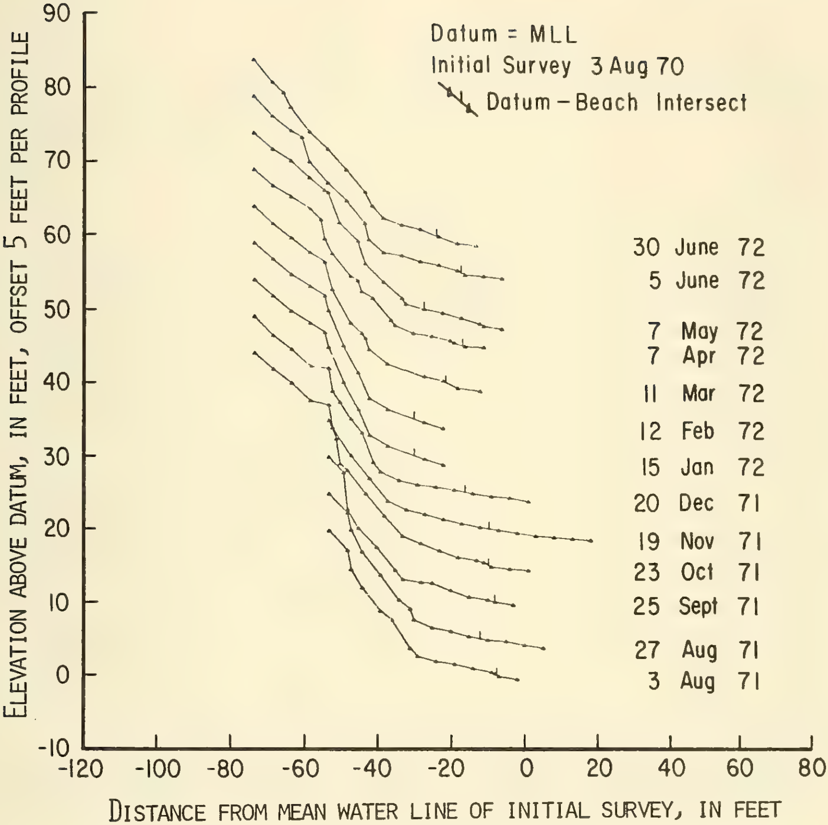

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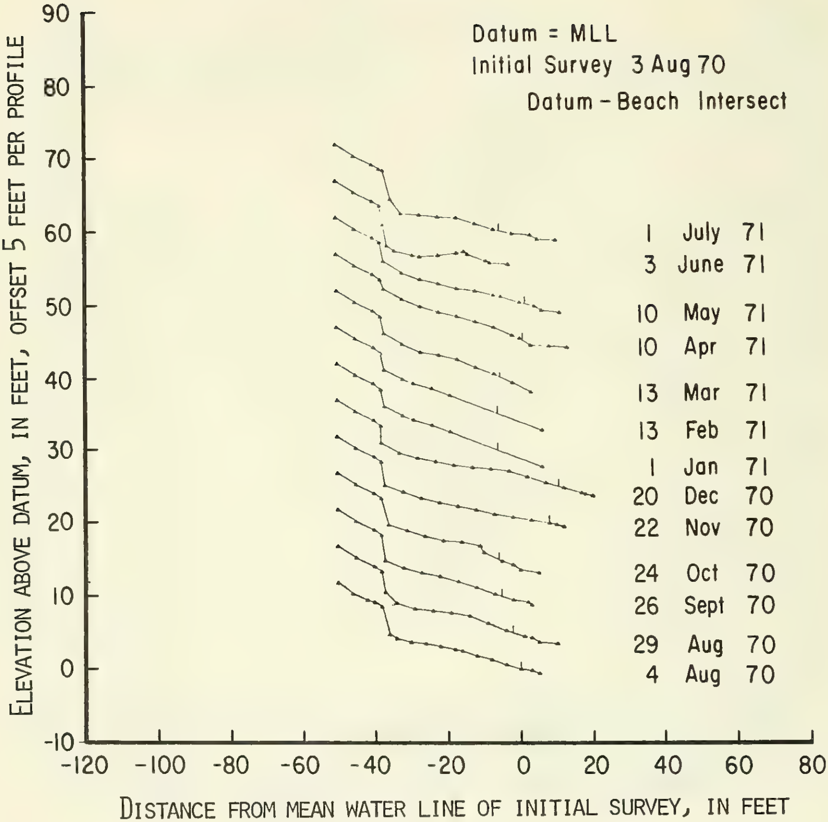

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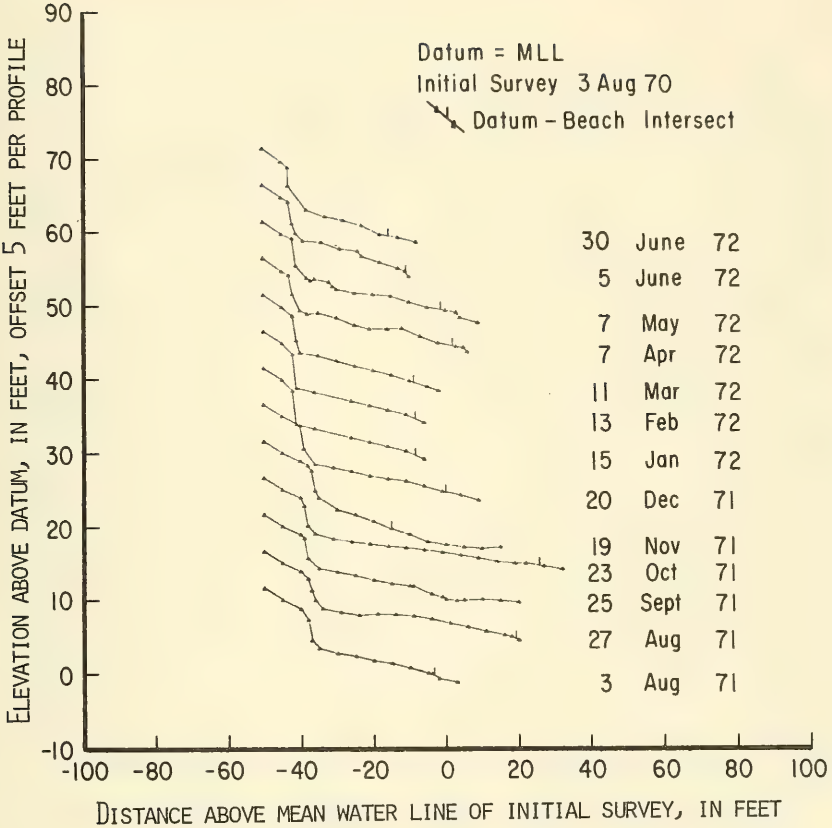

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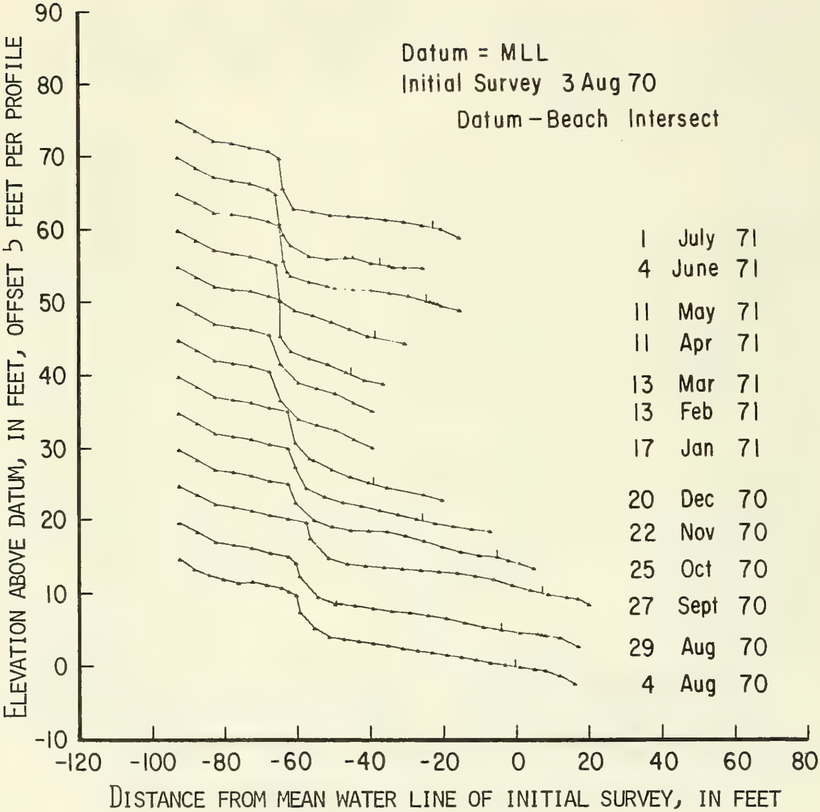

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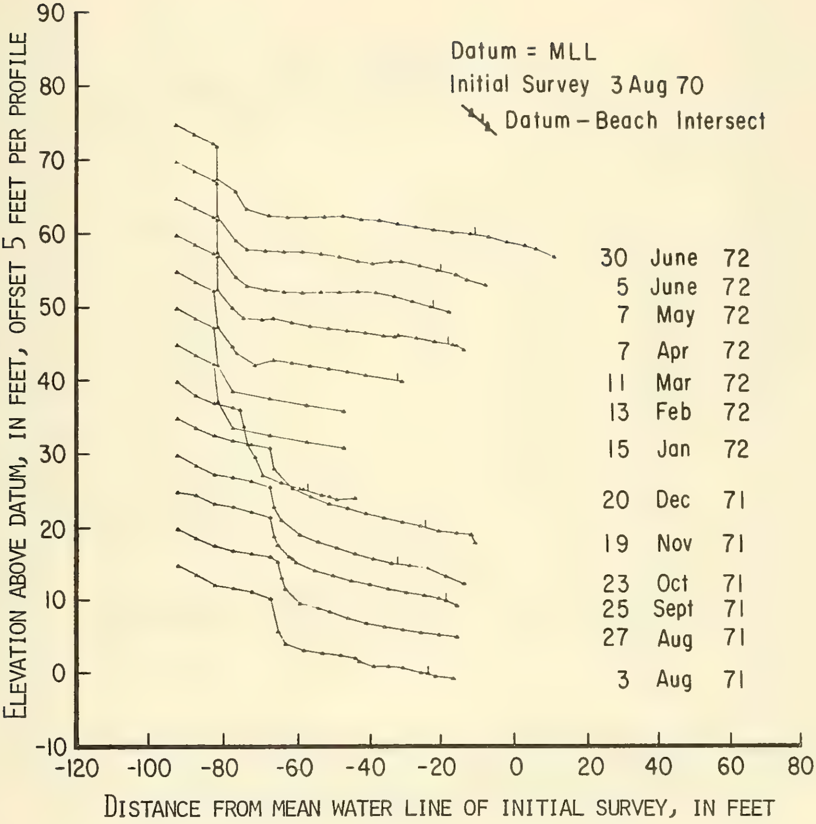

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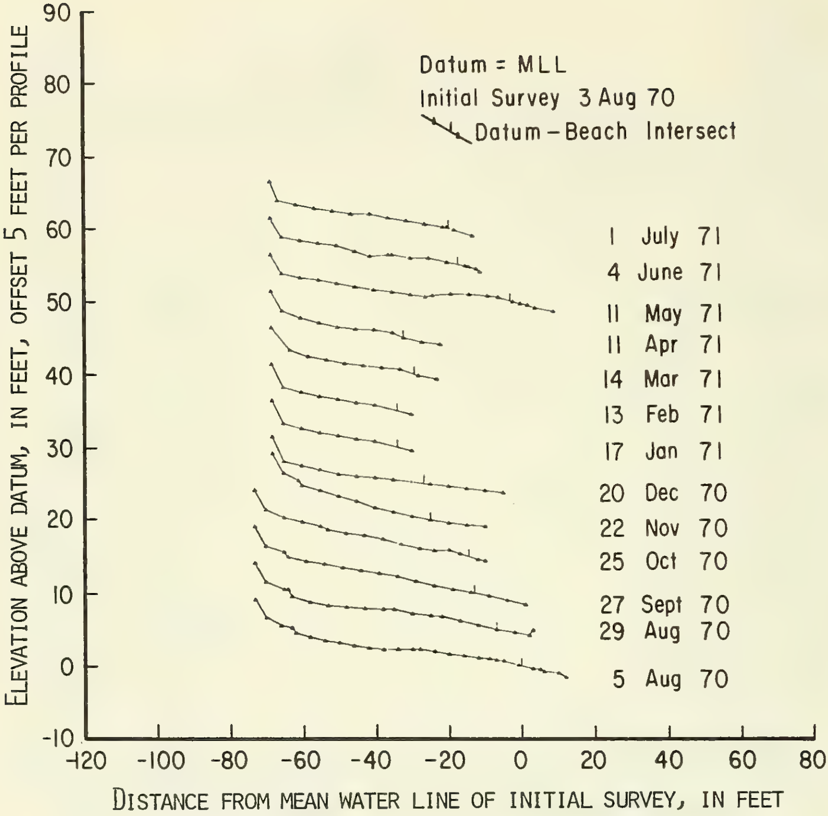

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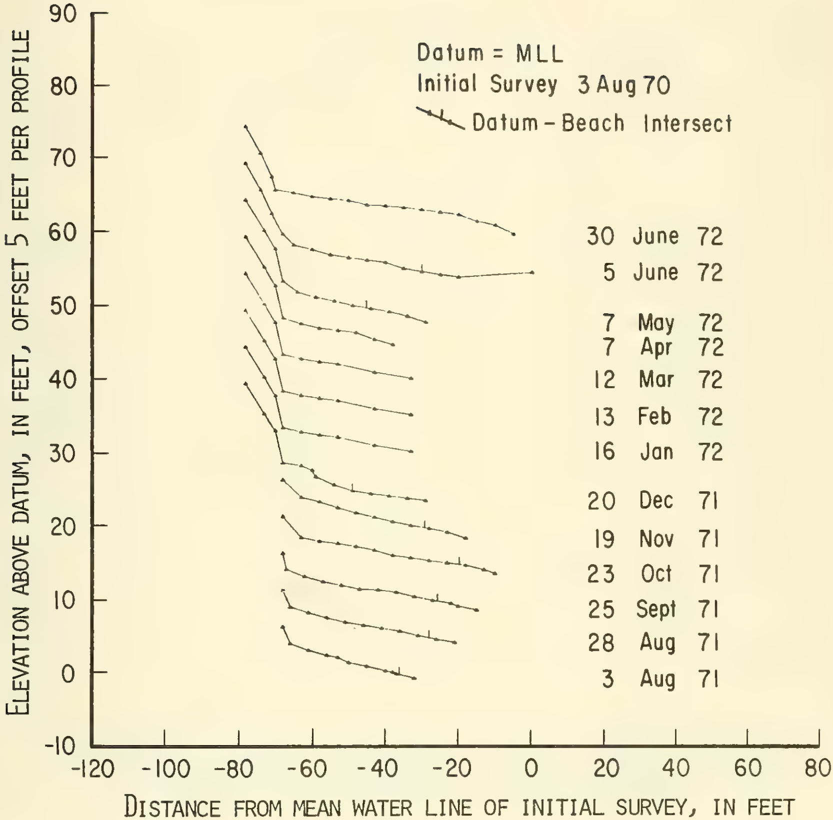

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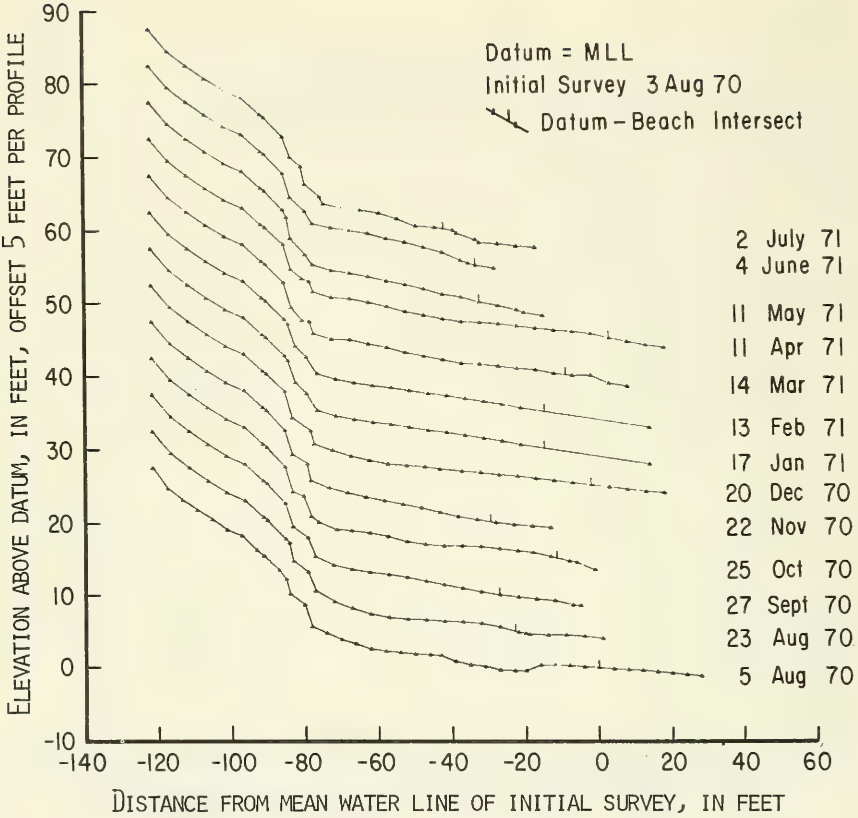

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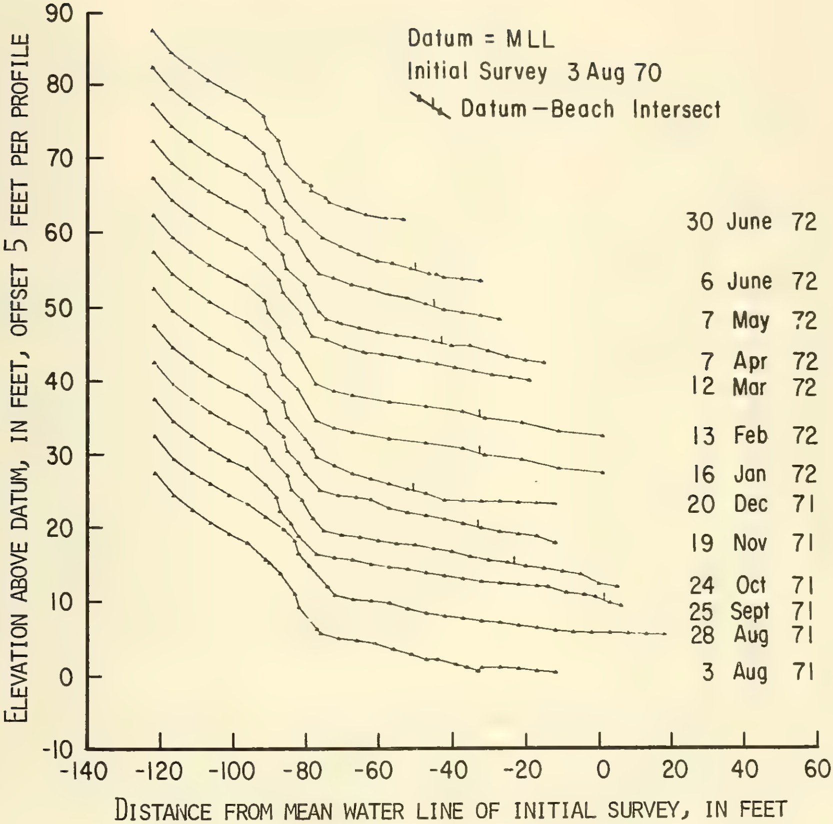

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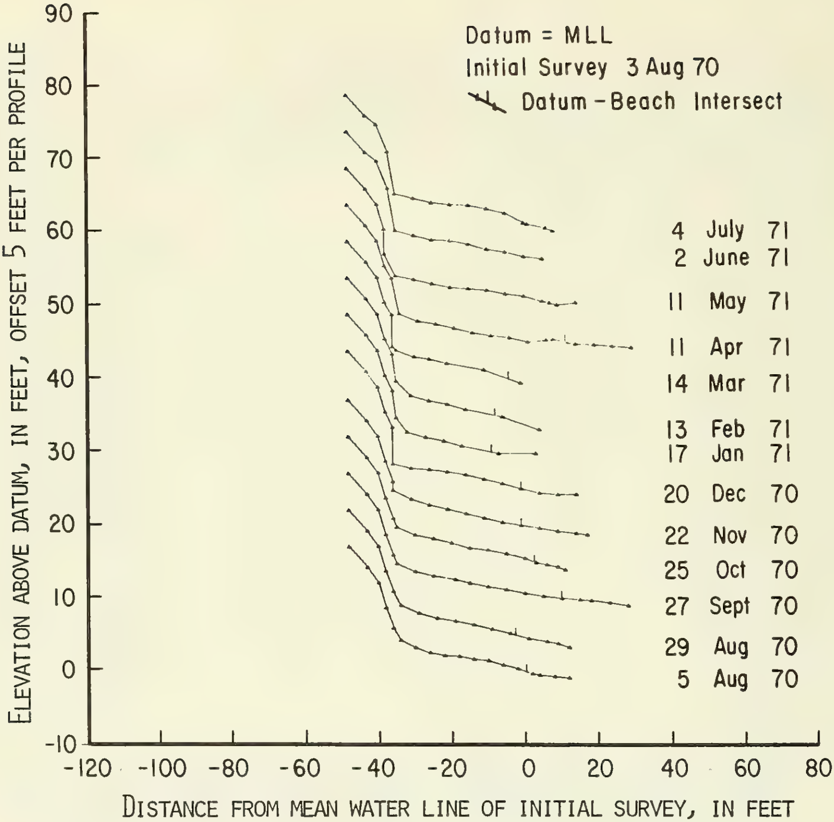

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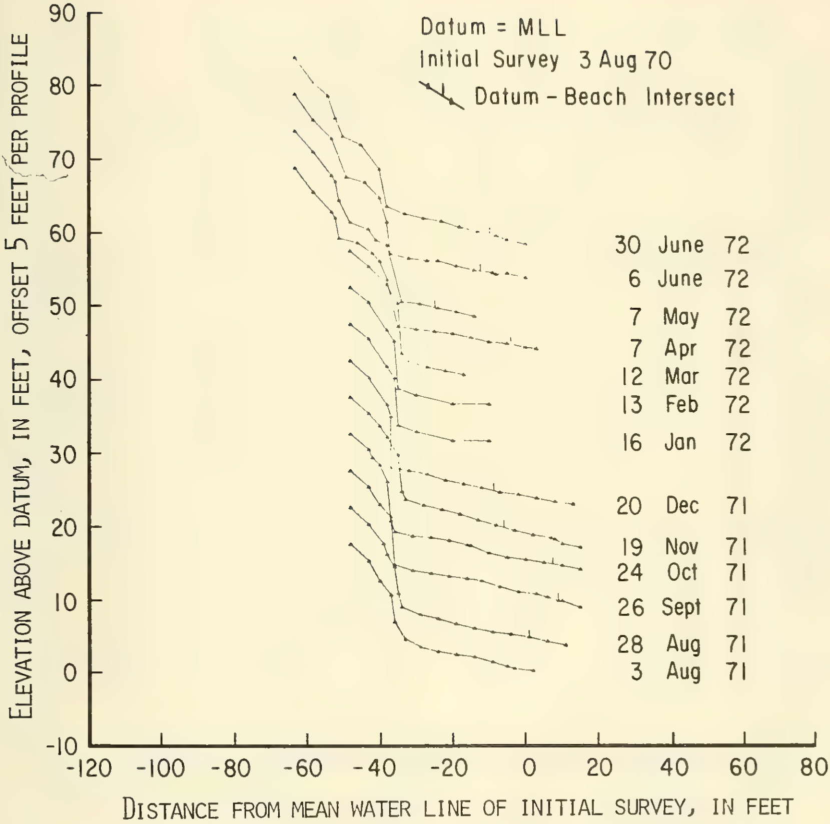

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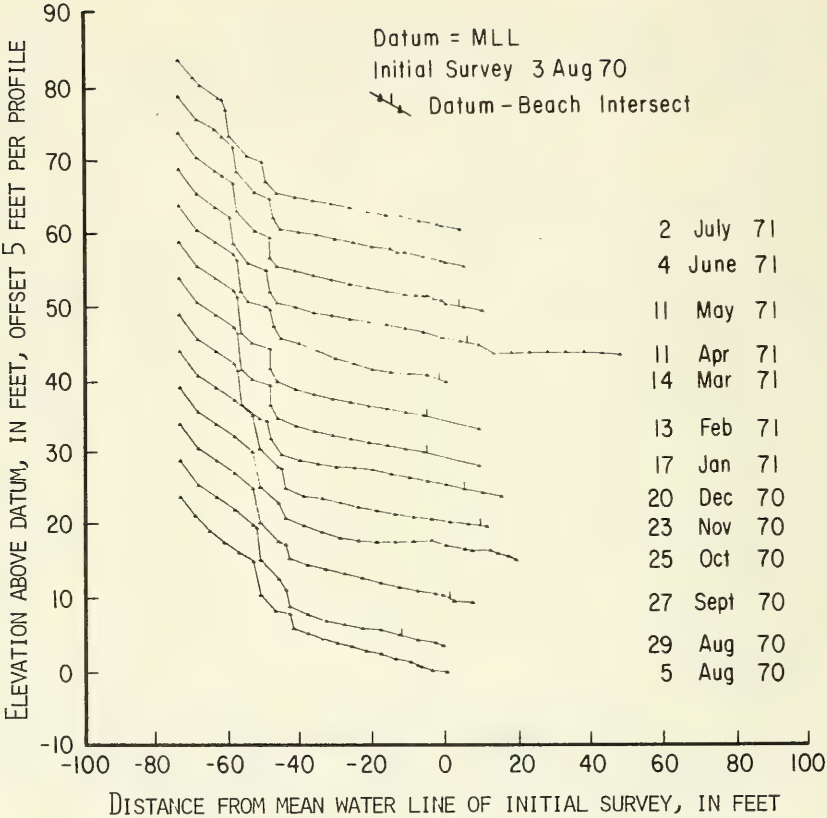

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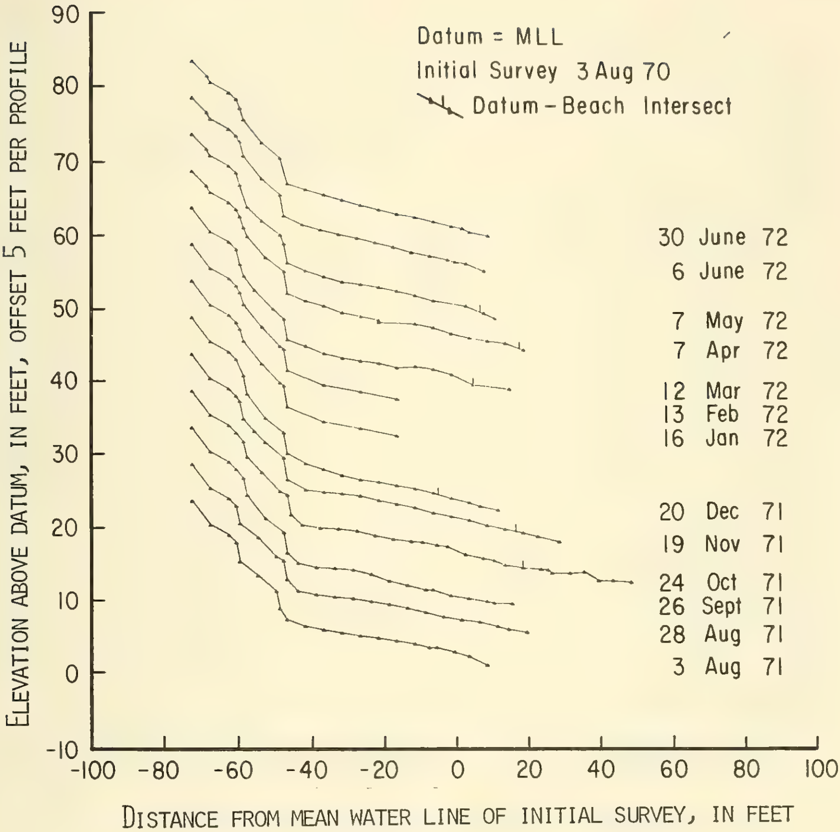
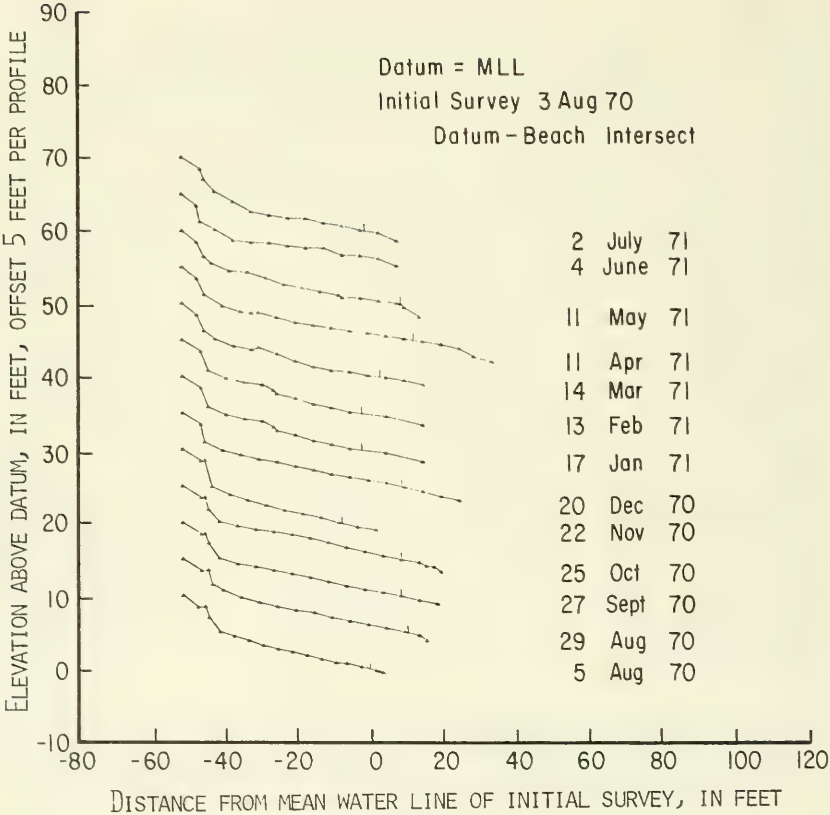


Changes at site 16.



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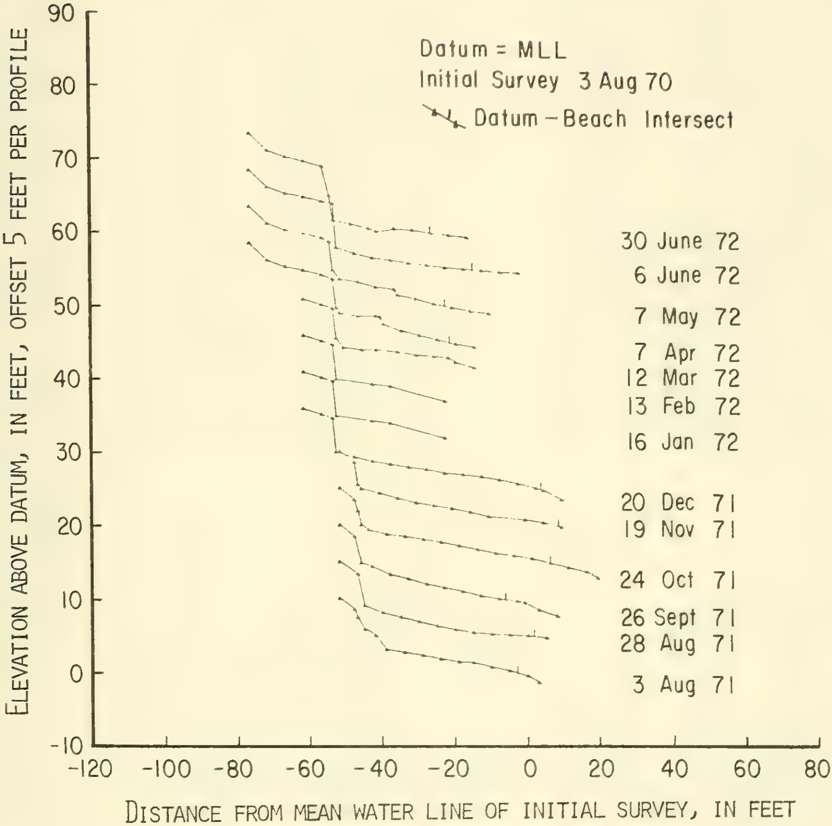

Changes at site 17.

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